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Soil Moisture

TECHNICAL REPORT

REMOTE MEASUREMENTS OF SOIL MOISTURE BY MICROWAVE RADIOMETERS AT BARC TEST SITE

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ABSTRACT

An experiment on the remote sensing of soil moisture content by microwave radiometers mounted on a mobile tower was carried out during October 1979 over bare and vegetated fields in a test of Beltsville Agricultural Research Center (BARC). Two microwave radiometers were used in the experiment, one of them at 1.4 GHz (L-band) and the other at 5 GHz frequencies. Both radiometers measured the field brightness temperatures over 10°-70° incident angles in vertical and horizontal polarizations simultaneously. Five types of fields were included in the measurements, namely, bare, 10-cm tall orchard grass, 30-cm tall orchard grass, soybean, and corn. Ground truth on soil moisture content and temperature, as well as the biomass of the vegetations was acquired in support of the microwave radiometric measurements.

This document describes the operational principle of the various sensors and the data system. It also gives a tabulation of the measured data, a brief discussion on the problems associated with the sensors, and a preliminary analysis of measured data. The results show that the measured brightness temperatures at both L and C bands decrease with the increase in soil moisture

content, in general agreement with the observations of the past. The presence of vegetation cover generally gives a higher brightness temperature than that expected from a bare field when the soil is not dry. As a consequence, the sensitivity of microwave soil moisture sensing is reduced.

REMOTE MEASUREMENTS OF SOIL MOISTURE BY MICROWAVE RADIOMETERS AT BARC TEST SITE

1. Introduction

In the development of the use of microwave radiometric techniques for the remote sensing of soil moisture it has been found that there are a number of factors which contribute noise to the signals. These factors include surface roughness, vegetation cover, soil temperature, and soil texture variations. In order to obtain an understanding of these effects and a means for estimating their magnitude a series of field experiments have been undertaken. These experiments involve the use of microwave radiometers operating from portable towers (cherry pickers) over small fields whose conditions are controlled and well monitored.

The objectives of these experiments are to provide data for verifying the applicability of radiative transfer models for predicting the microwave emission from soils and to obtain the data needed for parameterizing the effects of surface roughness, and vegetation cover which are very difficult to derive from first principles. In addition, frequent samplings of soil moisture contents down to the depth of ~ 1m combined with the radiometric measurements may demonstrate the usefulness of the soil moisture remote sensing of the surface layer for hydrologic modelling.

2. Microwave Sensor Systems

2.1. C-Band and L-Band Radiometers

2.1.1. C-Band Radiometer

The C-band radiometer is a switching type radiometer, commonly referred to as the Dicke type radiometer. Its block diagram is shown in Figure 1. The radiometer receiver is a Tuned Radio Frequency (TRF) type with noise figure of 3.1 db. The effective R.F. bandwidth of the radiometer and antenna is B=30 MHz centered at f_0=4.99 GHz. The effective integration time constant is 0.1 sec. Assuming 0.3 db loss per circulator switch (specification called for a maximum of 0.3

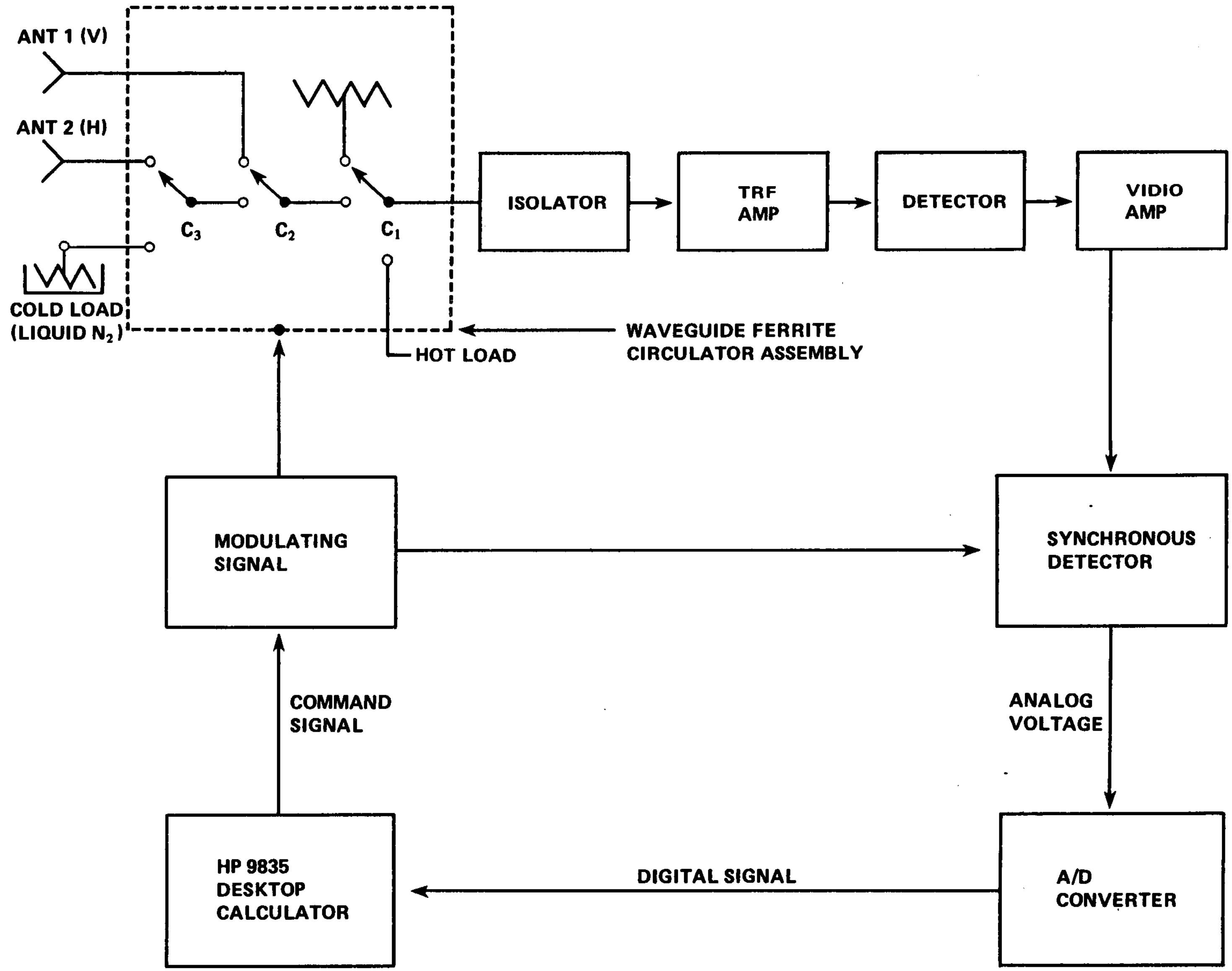

Figure 1. Schematic and Block Diagram of C-Band Microwave Radiometer.

db) the maximum total switch loss is about 1 db. The temperature sensitivity is about $\Delta T=0.85°K$. If η independent samples are taken and statistical averages performed, then the effective temperature sensitivity $\Delta T'$ becomes

$$\Delta T' = \Delta T/\sqrt{\eta} \tag{1}$$

The samples will be independent if the sampling interval is longer than 0.1 sec. During 1979 measurements, typically 50 samples were taken so that the effective temperature sensitivity of the average value should be $\sim 0.15°K$.

The radiometer has four modes of operation, two of them associated with the antenna signals (ANT1 for vertical and ANT2 for horizontal polarizations) and the other two with the hot and cold calibration loads. In the two antenna signal modes, the RF power from either polarization is transmitted to the circulator C, which oscillates (at about 1000 Hz) between the antenna and hot load positions. The net result is that the RF signal to the receiver is an amplitude-modulated wave whose envelope is a square-wave. This envelope is detected and amplified by the detector and vidio amplifier resulting in a square-wave whose amplitude is proportional to the difference in microwave brightness temperatures between the antenna and the reference hot load. This square-wave is turned into d.c. voltage (by the synchronous detector) Va whose value is also proportional to the difference in brightness temperatures of the antenna and the hot load. In the "cold calibration" mode , the radiometer measures the difference in brightness temperatures of the "hot load" and the liquid nitrogen soaked "cold load". This is achieved again by the oscillating switch C_1. The corresponding d.c. voltage is V_c. In the "hot calibration" mode C_1 is connected to the "hot load" port permanently (no oscillation) but the synchronous detector is still on. The radiometer in this case is comparing the hot load temperature to itself and the difference will be zero. However, to avoid (A/D) electronic circuitry peculiarity, an offset voltage of Vo = 0.3 volt is artificially introduced for the hot load output. The hot load temperature is maintained constant by a heater controlled by a proportional circuit and the ambient temperature of the whole radiometer enclosure is also maintained nearly constant by a heater and a feedback circuits.

The radiometer receiver is connected to different ports for the above modes by properly switching the three ferrite circulators connected in tandem. The circulator switches are so wired that in the two signal modes, the antenna that receives energy from a target also radiates energy at the cold load temperature, while the iding antenna radiates at the hot load temperature (This is not shown in the figure). For example, when the radiometer is in ANT2 mode it receives horizontally polarized energy from a terrestial target. At the same time the same horizontal antenna also acts as a radiator radiating energy from the cold load (due to the anisotropic nature of the circulator). Part of this energy, upon reaching the terrestial surface, might be scattered back to the same horizontal antenna, adding some error to the true target brightness temperature. The magnitude of this error depends on the backscatter coefficient of the target which decreases with increase in the angle of incidence θ (maximum at nadir). The fact that the antenna radiates at cold load temperature is designed to minimize this error which is sometimes referred to as radiometer image error. The idling antenna ANT1 radiates in vertical polarization at the hot load temperature. Since it is orthogonal to horizontal polarization in use the backscattered energy in horizontal polarization received by the radiometer will be negligibly small.

The sequence of mode change and the dwell time of each mode are controlled by commands from a Hewlett Packard Model 9835 Desktop Calculator. The calculator is programmed to cycle the radiometer through ANT1, hot load, ANT2, and cold load. Typically, the radiometer is commanded to stay in each mode long enough for the calculator to take 50 samples.

2.1.1.2 Antenna

The antenna used for the C-band radiometer during the 1979 measurement period is a dual polarized slotted waveguide planar array. The two orthogonally polarized beams are formed independently by two sets of interlaced waveguide elements. The bandwidth of the antenna is $\pm$ 15 MHz centered at 499 MHz. The antenna aperture is 80 cm X 77 cm and beamwidth is $\sim 6.5°$ at half-power points. The beam efficiency is about 96% with maximum side lobe 24 db below main lobe. However, the maximum side lobe occurs at about 80° away from the main lobe which itself is about 37° from broadside. As a result, for nadir viewing (θ=0°) the planar array is tilted 37° in elevation angle. The installation geometry of the array antenna on the Cherry-picker boom is such that as soon as θ is increased from 0°, the maximum sidelobe begins to point toward the sky. The geometrical relationship among the planar array antenna, and its main and sidelobes are depicted in Figure 2. The fact that the maximum side lobe looks at the sky may be the reason why the C-band radiometer observed a few degrees Kelvin cooler brightness temperature compared to L-band in most of the 1979 data set. This was not so in the 1978 measurements when the antennas used for C-band radiometer were corrugated horns.

2.1.2. L-Band Radiometer

2.1.2.1. The Radiometer Electronics

The L-band microwave radiometer used during the 1979 BARC field experiment was built by AIL (Airborne Instrument Lab. of Long Island, N.Y.) under NASA contract NAS 5-24244 for Goddard Space Flight Center (AIL Model No. 351). Key parameters of this radiometer are shown in Table 1. The radiometer is also of Dicke type with 1 KHz square-wave modulating frequency. The L-band radiometer block diagram is similar to that of C-band radiometer, however, the switch block is made of PIN diodes rather than ferrite circulators. The R.F. insertion loss through the switch is about 0.75 db except for the "hot load" mode which is about 0.9 db. The expected temperature sensitivity (ΔT) based on 0.1 sec integration time and 27 HMz bandwidth is 0.93°K. There are five ports in the switch block, four of which correspond to the four modes, namely antenna vertical, antenna horizontal, cold load calibration, and hot load calibration. The fifth port is a "reference load" port. Both reference load and hot load are coax termination maintained at 43°C temperature. The 1 KHz modulating signal is on for all four modes. The modulated R.F. signal from the switch block is amplified by a TRF amplifier and turned into a d.c. voltage by an envelope detector and a synchronous detector. The amplitude of the d.c. voltage is proportional to the difference in brightness temperature between any of the four ports (ANT V, ANT H, hot, or cold) and

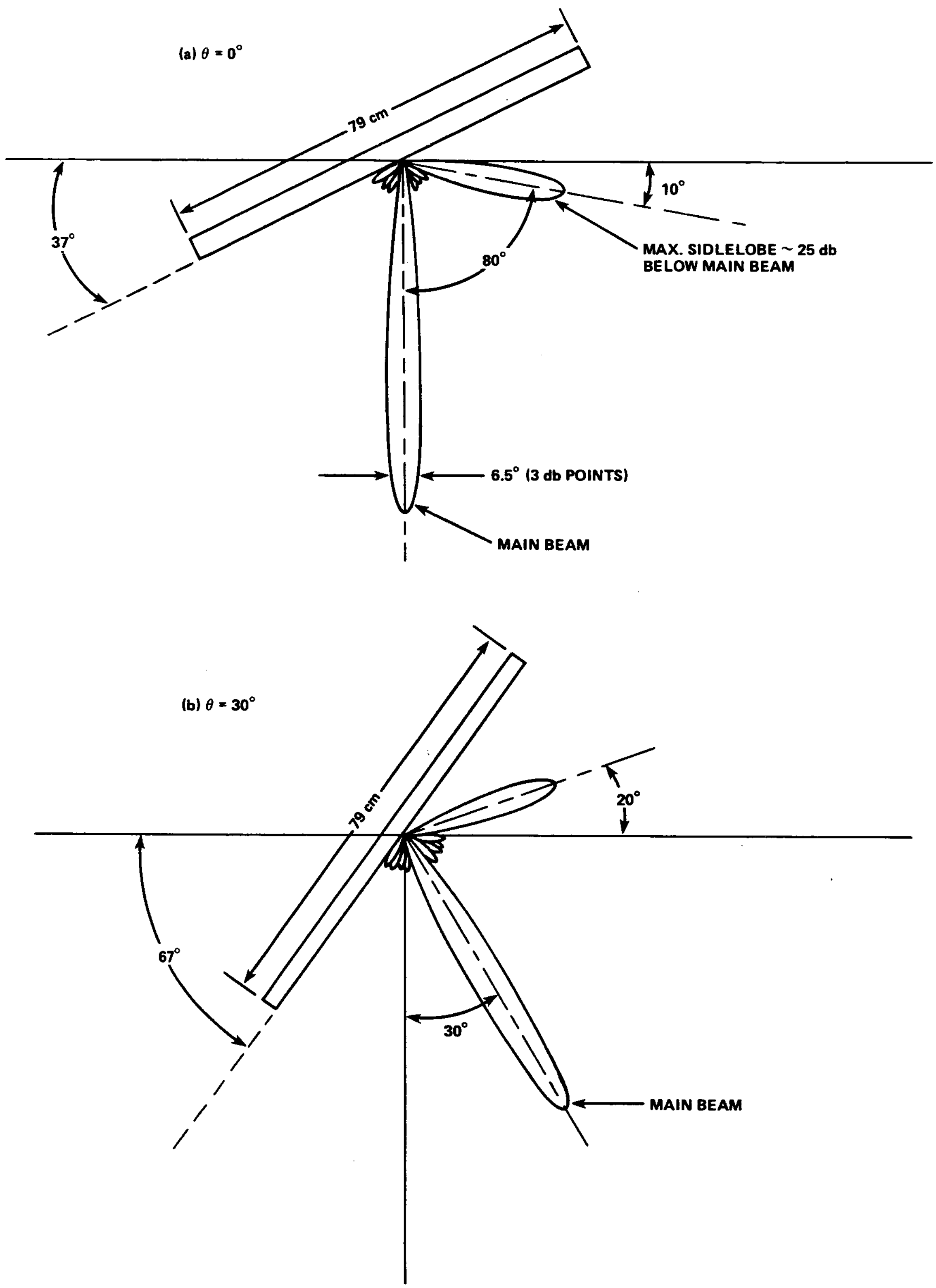

Figure 2. C-Band Phased Array Antenna Main Beam and Sidelobe Positions.

the reference load. The switch timing is controlled by commands from the HP desktop calculator. The output analog voltage is sampled (A/D) and fed into the same HP calculator for processing and storage. The L-band radiometer has a built-in automatic gain control and is therefore more stable in the output voltage compared to that for the C-band radiometer.

2.1.2.2 Antenna

The L-band radiometer antenna used in the 1979 field measurements is a prime focus fed parabolic dish of 122 cm in diameter with a focal length to diameter ratio of 0.32. The dual-linear polarizations are produced by two cross dipole feeds backed by a cup-shaped plate. The 3-db beamwidth is about 10°. First null to null beamwidth is about 25° and the maximum sidelobe is about 18 db below the main lobe. Gain is 15.44 db, corresponding to an aperture efficiency of 56%. Maximum cross polarization lobe is about 25 db below the main lobe. The antenna feeds are connected to the radiometer by 1.52 m coax cables with insertion loss of about 0.3 db.

2.2. Data System

The data system consists of three major components, all of them are products of Hewlett Packard Company. They are the HP 3455A Digital Voltmeter, the HP 3495A Programmable Scanner/Multiplexer, and the 9835A Desktop Calculator with a HP 9876A Thermal Graphics Printer. The digital voltmeter provides measurements of the incoming antenna signal as well as the housekeeping data of various line temperatures and the antenna incident angle. The antenna signals are measured in volts, signals from the inclinometer and line temperature sources are measured in ohms. Conversion to brightness temperatures from voltages, physical line temperatures and the sensors' incident angle is made automatically by the desktop calculator. Measurements by the digital voltmeter are controlled by the 48 channel scanner. The antenna and housekeeping signals are each identified with a particular scanner channel. In normal operation, both the scanner and the digital voltmeter are automatically controlled by the desktop calculator. The calculator selects a certain channel, and then takes in the corresponding signal measured by the digital voltmeter as input for processing and recording.

The desktop calculator is a 16-bit word machine which controls the above mentioned peripheral devices required for the experiment. It has 49,962 bytes of core memory. The program used in running the experiment and processing the data is written in Basic Language.

2.3. Radiometer System Calibration

2.3.1. Calibration Approach

Both L- and C-band radiometers are of Dicke type switching radiometers. The main merit of a Dicke radiometer is that it has a better (smaller value) system sensitivity ΔT. An "ideal" (total power) radiometer with system noise temperature T_s, bandwidth B, and integration time t will have a

$$\Delta T^i = \frac{T_s}{\sqrt{Bt}} \tag{2}$$

A Dicke system with square-wave modulation (with same system noise temperature T_s) will have a temperature sensitivity of

$$\Delta T = \sqrt{4\,(\Delta T^i)^2 + \left(\frac{\delta G}{G}\right)^2 (T_A - T_{ref})^2} \tag{3}$$

where T_{ref} is the reference load temperature and T_A is the antenna temperature. G is the system gain and δG the gain fluctuation. If T_{ref} is chosen to be $\simeq T_A$, then ΔT approaches its minimum value of

$$\Delta T_m = 2\,\Delta T^i \tag{4}$$

The temperature sensitivity referred to in Section 2.1.1. corresponds to ΔT_m here, i.e., the gain fluctuation is not included. In reality of course T_A varies and $T_A \neq T_{ref}$. For example, in the L-band radiometer, $T_{ref} = 43°C = 314°K$ and T_A may vary from 150°K to 270°K. The term $\delta G/G$ is in the order of 10^{-2}. Let $T_{ref} - T_A = 100°K$, then the second term in Eq. (2.3.2.) is of the order of 1. The first term is 2 ΔT^i = 0.93°K (for 4.4 db total system noise, 30 MHz bandwidth, and 0.1 sec integration time) and the overall ΔT is 1.37°K. For a typical total power radiometer, the temperature sensitivity ΔT^t is given by

$$\Delta T^t = \sqrt{\frac{1}{Bt} + \left(\frac{\delta G}{G}\right)^2}\; T_s \tag{5}$$

If $\delta G/G = 10^{-2}$ and T_s = 808°K (4.4 db noise figure), then ΔT^t = 8.1°K. This clearly demonstrated the power of the modulating radiometer in reducing ΔT.

The Dicke radiometer effectively reduce the gain fluctuation term of ΔT. ΔT can be improved further by reducing δG with frequent calibration (frequent determination of G, once in every calibration cycle). In this way δG is limited to the fluctuation between two calibrations. The power spectrum of δG vs f ($\tau = \frac{1}{f}$ is the period of calibration) has a $1/f$ dependence. Thus by making f larger, one can further reduce ΔT. It is for this reason that both C- and L-band microwave radiometers have built-in calibration loads. These calibration loads are two microwave terminations, one is kept at T_{ref} temperature (hot load) and the other at liquid nitrogen temperature (cold load). Each set of antenna temperature measurements is followed by two internal calibrations (a hot calibration and a cold calibration). This internal calibration allows one to determine the system gain frequently. In principle, the internal calibration is sufficient to determine the antenna temperature if other system parameters such as ohmic loss of the switches and various transmission lines are accurately known. In reality, however, most of these parameters are not easily and/or accurately determined. Therefore, an "external" overall system calibration procedure is necessary.

2.3.2. Calibration Procedure

Both C- and L-band radiometers are calibrated in the same way. The calibration is carried out by making measurements of two targets of known microwave brightness temperature. Since the radiometer is a linear device (or very nearly so) in the sense that the input brightness temperature T_B to the antenna is linearly related to the output voltage. The two-point calibration will uniquely determine its calibration line. This is true provided the ambient temperature remains constant.

The two known "targets" used for both L- and C-band radiometer calibrations are the clear sky and a layer of Eccosorb slab (Eccosorb is the trade name of a styrofoam type material sprayed with carbon powder, commonly used in anechoic chamber, made by Emerson and Cumming Co.). The brightness temperature of the clear sky can be accurately calculated to be ~ 4.98°K at L-band and 5.20°K at C-band by assuming a U.S. standard atmosphere model. For the Eccosorb slab the brightness temperature is about equal to its physical temperature (absorption coefficient of 0.99) which can be easily measured during calibration. Radiometer system calibrations with these two known targets are made in each day of field measurements. In addition, the system calibrations are also checked by occasional measurements of the brightness temperature of the calm water surface. Figures 3 and 4 show the calibration results for the L-band and C-band radiometers respectively. In both figures, the measured or calculated brightness temperature in both vertical and horizontal polarizations of the known targets are plotted against the normalized antenna voltage (system gain variations are largely eliminated by normalization). The measurements over the calm water surface cover the θ range from 10° to 60°. The θ=0° measurements are discarded because of the radiometers' self emission problem discussed previously. Since the brightness temperature of the clear sky is not expected to change much in the day to day operation, only the average values of the many calibration measurements are entered into the figures. It is clear that the radiometric responses of both L- and C-band radiometer systems are linear over the wide brightness temperature range of 5°K – 300°K. The regression results of the calibration data in Figures 3 and 4 are used for the derivation of brightness temperatures in the field measurements.

2.3.3. The Calibration Equations

The calibration switch block of either the L-band or the C-band radiometer can be represented by a schematic diagram as shown in Figure 5. The output voltage from the radiometer and the

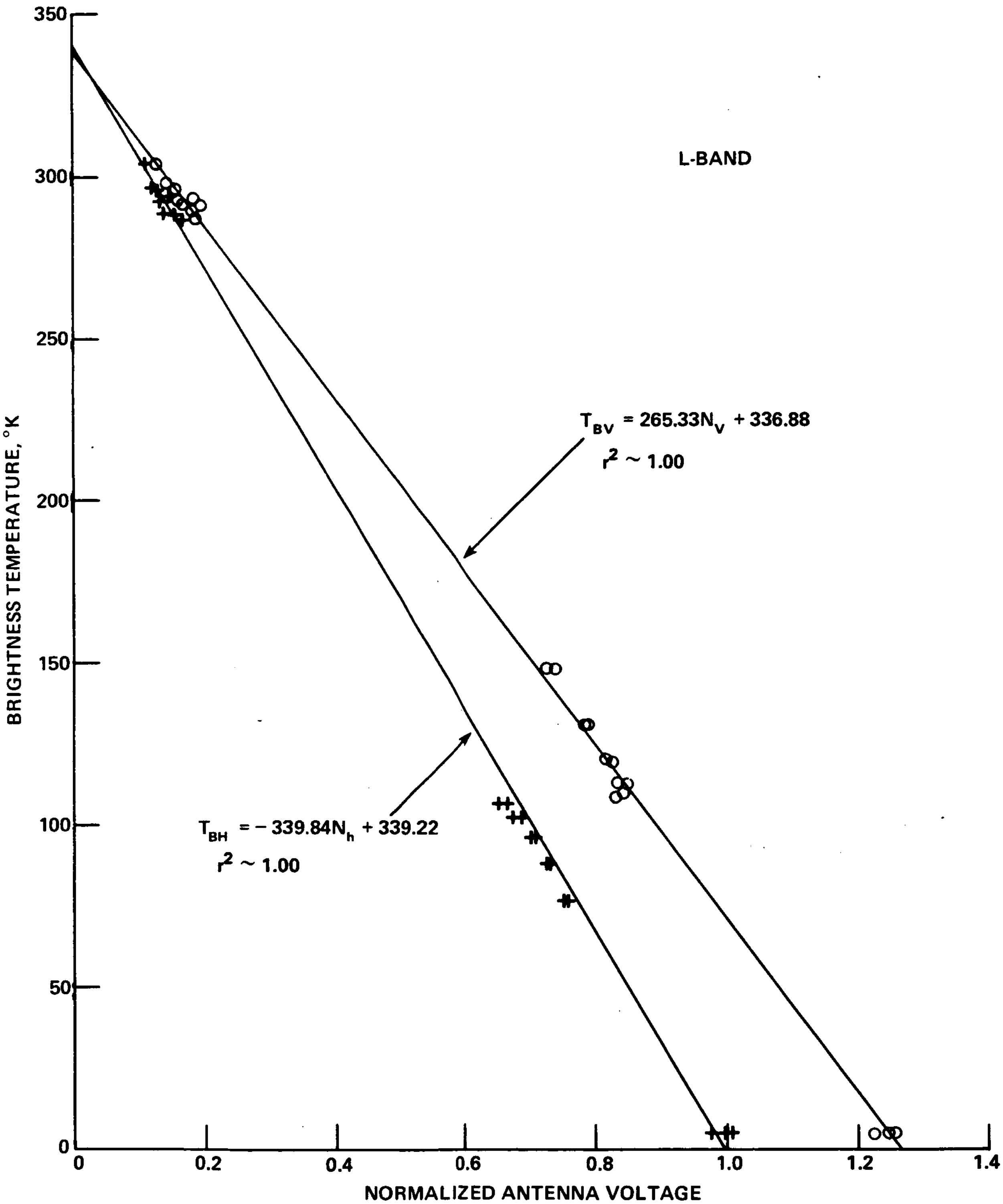

Figure 3. The L-Band Calibration Data and Results

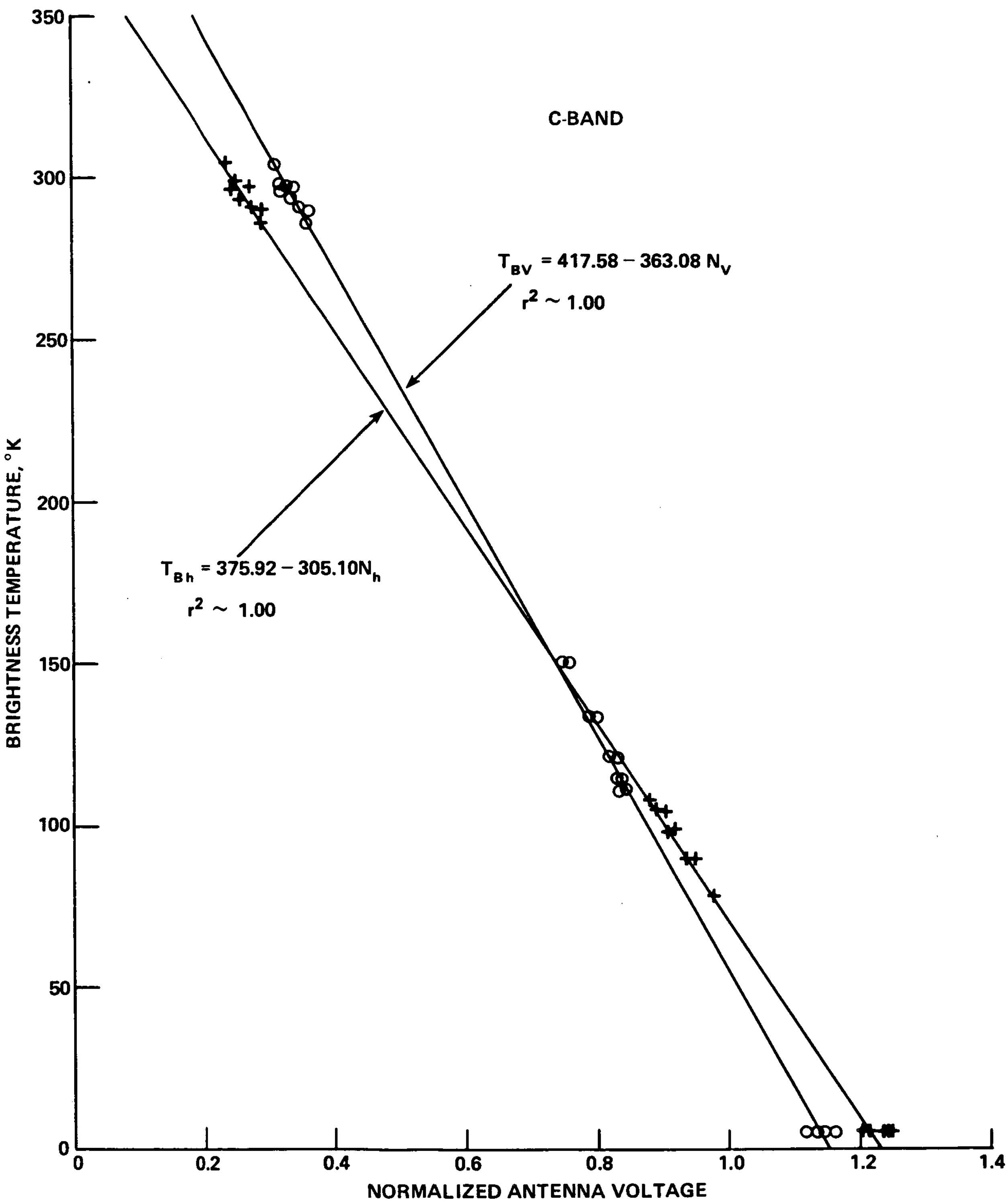

Figure 4. The C-Band Calibration Data and Results

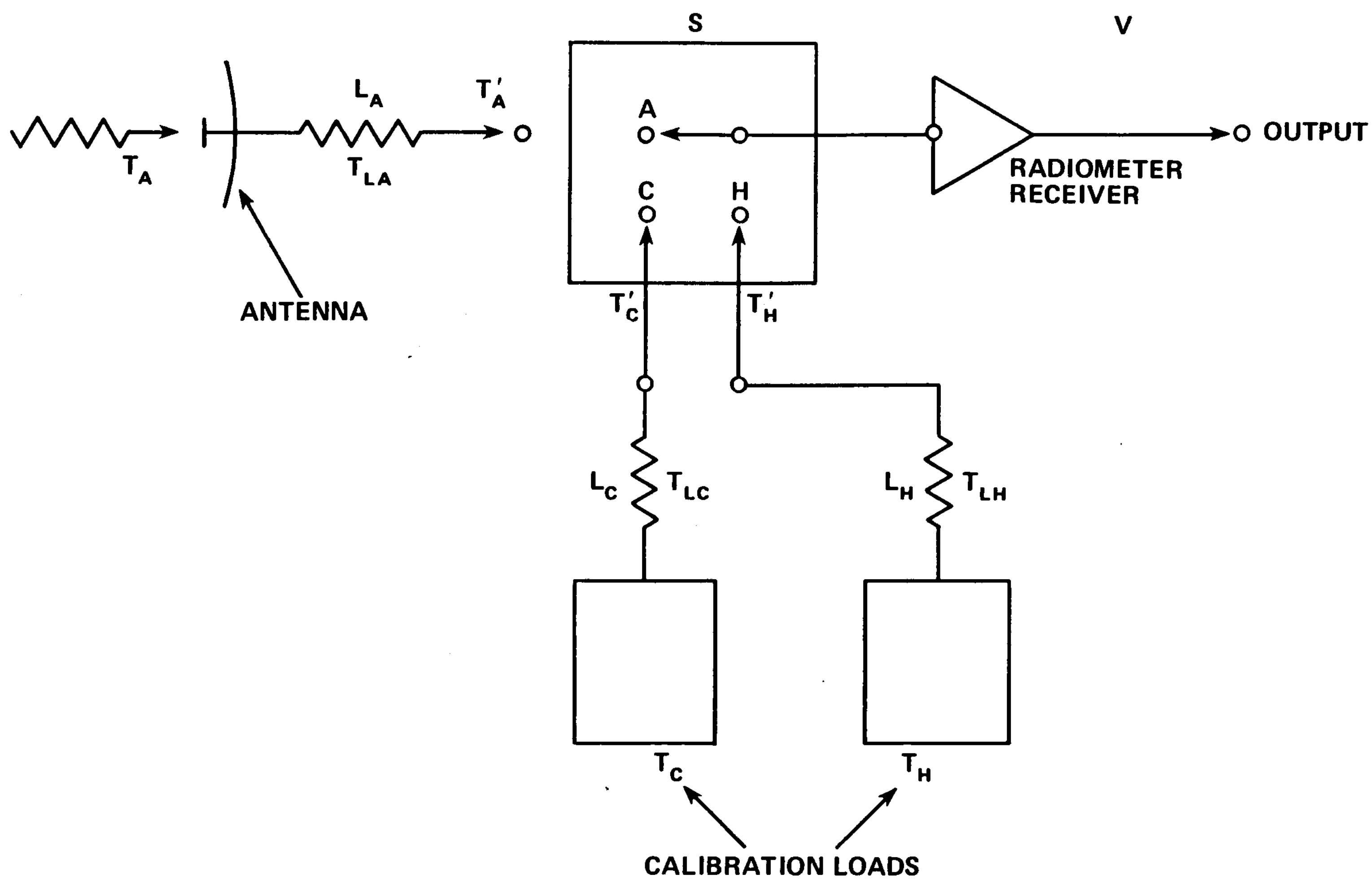

Figure 5. The Block Diagram of the Radiometer Calibration Switch.

input temperature to the switch block are related by a linear equation:

$$\frac{V_A - V_H}{T_A{}' - T_H{}'} = \frac{V_H - V_C}{T_H{}' - T_C{}'} \tag{6}$$

Let $N = \dfrac{V_A - V_H}{V_C - V_H}$, (7)

Then,

$$T_A{}' = (1 - N)\, T_H{}' + N T_C{}' \tag{8}$$

Since

$$T_A{}' = \frac{T_A}{L_A} + \left(1 - \frac{1}{L_A}\right) T_{LA}, \tag{9}$$

$$T_C{}' = \frac{T_C}{L_C} + \left(1 - \frac{1}{L_C}\right) T_{LC}, \tag{10}$$

and

$$T_H{}' = \frac{T_H}{L_H} + \left(1 - \frac{1}{L_H}\right) T_{LH} \tag{11}$$

one can combine Eqs. (7) through (11) to obtain

$$T_A = Nm + b \tag{12}$$

where

$$m = L_A \left\{ \left[\frac{T_C}{L_C} + \left(1 - \frac{1}{L_C}\right) T_{LC}\right] - \left[\frac{T_H}{L_H} + \left(1 - \frac{1}{L_H}\right) T_{LH}\right] \right\} \tag{13}$$

$$b = L_A \left\{ \left[\frac{T_H}{L_H} + \left(1 = \frac{1}{L_H}\right) T_{LH}\right] - T_{LA} \right\} L_A + T_{LA} \tag{14}$$

Note that the antenna temperature T_A and the normalized voltage N are linearly related. By making two measurements N_1 and N_2 of two known targets (with brightness T_{A1} and T_{A2}), the slope m and intercept b can be determined. m and b will remain constant as long as the terms in Eqs. (13) and (14) do not change with time. Eq. (12) is consistent with the calibration results shown in Figures 3 and 4.

The loss parameters in (13) and (14) such as L_A, L_H, and L_C are not expected to change. As a first approximation, let

$$T_{LA} \simeq T_{LC} \simeq T_{LH} \simeq To = \text{Ambient temperature}$$

then

$$m = \left[To\left(\frac{1}{L_H} - \frac{1}{L_C}\right) + \left(\frac{T_C}{L_C} - \frac{T_H}{L_H}\right)\right] L_A \tag{15}$$

and

$$b = \left[To\left(1 - \frac{L_A}{L_H}\right) + \frac{T_H}{L_H} L_A \right] \tag{16}$$

Since T_H and T_C are constant,

$$\frac{\delta m}{\delta To} = L_A \left(\frac{1}{L_A} - \frac{1}{L_C}\right) \tag{17}$$

$$\frac{\delta m}{\delta To} = \left(1 - \frac{L_A}{LH}\right) \tag{18}$$

For C-band radiometer,

L_H = 0.3 db = 1.07152

L_C = 1 db = 1.2589

L_A = 1.4 db = 1.3804

Hence, $\frac{\delta m}{\delta To} = 0.19°K$, $\frac{\delta b}{\delta To} = -0.29°K$,

Since $77°K = T_C < T_A < T_H = 310°K$, $O < N < 1$. Assuming a typical value of $N \simeq 0.5$, the sum of two terms will amount to about $-0.2°K$ per °K increase in ambient temperature. After a proper warmup, the ambient temperature hardly changes more than 10°K during the course of one day's experiment. Over all the measurements made in October 1979, the recorded ambient temperatures are found not to differ by more than 15°K. Therefore, the maximum calibration error will be less than 3°K even if the ambient temperature change is not corrected for.

3. Field Operations

3.1 Field Description

A field of Elinsboro sandy loam soil located on the USDA Beltsville Agricultural Research Center was selected as the test site for this study. The layout of the test site is shown in Figure 6. The microwave radiometer measurements were carried out only over plots 5, 6, 7, 8, and 10, and the surrounding ground planted with orchardgrass. These plots were 18.28 m × 18.28 m in size. Plots 7, 8, and 10 were smooth bare fields. Plot 5 was planted with corn on May 18 and plot 6 with soybeans on June 12. The cultivars Dekalb XL64A, York, and Pennlate were used for corn, soybeans, and orchardgrass crops, respectively. Prior to planting, the soil was limed and fertilized according to recommended rates. All tillage and planting were accomplished by using conventional methods. No additional tillage was required during the growing season since herbicides were applied at planting to control weeds. The corn and soybeans were planted in an East/West direction. Row spacing was 76 cm between rows and approximately 23 cm within the row for corn. For soybeans, the spacing was 61 cm between rows and approximately 5 cm within the row. The orchardgrass field was divided into two vegetation levels; one-half was kept at a height of 5 to 10 cm throughout the growing season whereas the other half was allowed to grow to a height of about 30 cm before harvesting.

The plots with bare soil were kept free of vegetation by spraying periodically with the herbicide paraquat. The corn and soybean crops had reached the state of physiological maturity of their grains and were in the process of vegetative dry down during the period of the radiometric measurements.

3.2 Sensor Operations

There were two trucks involved in the radiometric field measurements. One of them is a cherry picker with a 10-m boom. Both the L- and C-band radiometers with their respective antennas were secured to a platform which was tightly fastened to the end of the cherry picker crane. The other truck was an army van which housed the rest of the electronic equipment required in the

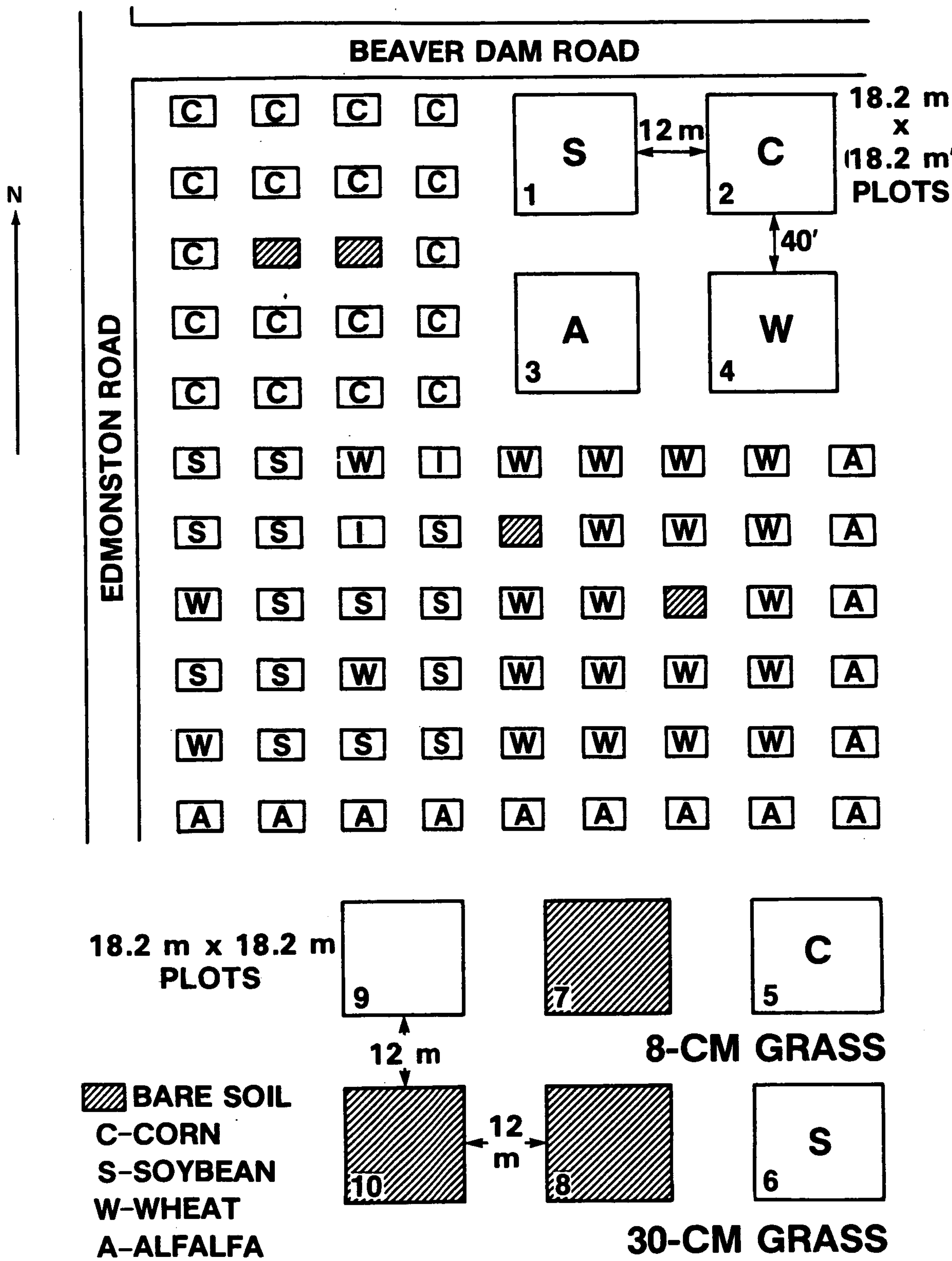

Figure 6. Layout of the Test Site for Microwave Radiometric Measurements.

measurements, such as the control panel, digital voltmeter, scanner, and the desktop calculator. An inclinometer was mounted on the platform and the signal from the inclinometer was fed to the desktop calculator so that the incident angles of the sensors could be monitored. A Dewar container was mounted adjacent to the radiometers in the platform which provided the cold reference load at 77°K liquid nitrogen temperature as discussed previously. A thermocouple was installed in the Dewar which served as an indicator of the level of the liquid nitrogen. In general, the Dewar container had to be refilled with liquid nitrogen in approximately two to three hour intervals.

At the beginning of each day's experiment, the radiometers were turned on and stabalized by allowing them to warm up for about 1-2 hours before the actual radiometric measurements took place. The radiometric measurements over a given field were made over incidence angles from 0° to 70° in 10° steps. The radiometer systems were maneuvered such that the main beams of the radiometer antennas always aimed at the same spots regardless of incidence angles. This maneuvering was accomplished by placing a marker on a spot which was then monitored by a TV camera mounted on the radiometer platform. Measurements by this approach minimizes the variations in the radiometric outputs due to the field inhomogeneities.

Eccosorb slabs and sky calibration were made at least once in each day's measurements. In the sky calibrations, the radiometers were turned to the zenith direction at times when the sun was not directly in view. In the Eccosorb calibrations, 12 pieces of 0.91 m X 0.91 m square and 23-cm thick Eccosorb slabs were spread over the grassland to form a layer of 2.74 m X 3.64 m rectangular absorber. Both C-band and L-band radiometer antennas were kept pointed in the nadir direction and as close to the absorber as possible. The absorption coefficient at 1.4 GHz of a layer of Eccosorb slab was about 98-99%. Of the remaining 1-2%, the transmission coefficient was found to be a more dominant factor than the reflection coefficient. Therefore, the contribution from the radiometers' self-emitted energy backscattered from the Eccosorb slabs was negligible. Since the difference in brightness temperatures between the

Eccosorb slabs (which is approximately equal to physical temperature) and the grassland was found to be no more than 60°-70°, the error introduced in the calibration due to transmission could not be more than ~ 1.5°K.

3.3. Soil Sampling

Both soil moisture and temperature ground truth informations were acquired simultaneously with the radiometric measurements over a given field. The soil moisture sampling was made at the depths of 0-2.5 cm, 2.5-5.0 cm, and 5-10 cm with a standard 2.2 cm diameter tube soil sampler. The soil samples were weighed and then dried in a microwave oven inside the van so that the moisture content in percent of dry soil weight could be compared with radiometric measurements immediately. The soil temperature was measured only at the depths of 0-2.5 cm and 10-12.5 cm. On two occasions when the soil of a bare field was dry so that there was a large moisture gradient near the surface, the ground truth of soil moisture in the top 0-0.5 cm layer was also taken. In addition, the ambient temperature reading 2.5 cm above the surface was recorded. Ground truth acquisitions were made twice during each radiometric scan over a given field, and took about 40 minutes. The calibrated radiometric measurement data and the associated ground truth information for all fields are tabulated in Appendix A. More extensive soil moisture sampling was also made (see next section) but not necessarily in concurrence with the radiometric measurements.

A few soil density measurements were taken over top the 2.5 cm of each field during the entire month of the measurement program. The device used for the density sampling was a 2.5 cm tall, 5 cm in diameter cylindrical tube of aluminum. With the exception of the short grassland, all the other fields had about the same average density of 1.47 gm/cm³. The ground under the short grass had a higher density of ~ 1.60 gm/cm³ due to heavy traffic.

4. Extensive Ground Truth Acquisition and Processing

4.1 Soil Moisture Sampling

Extensive water balance data were collected on each of the three plots to conduct daily water balance calculations and soil water profile models. The emphasis of the data collection activities was on the soil moisture. Soil moisture was determined by several methods at up to 6 locations and at up to 10 depths per plot. Climatic data for determining rainfall input and evapotranspiration were collected at a Class A weather station set up specifically for these experiments. For these experiments it was assumed that surface runoff would be zero; therefore the water balance was estimated for the following:

$$P = ET \pm \Delta SM - GW - RO \qquad (17)$$

where P = daily rainfall input

ET = daily evapotranspiration

ΔSM = loss or gain in soil moisture

GW = deep seepage to ground water

RO = surface runoff

The GW Term was also assumed to be zero. Except for exceedingly wet periods, this assumption is reasonable for the growing season when evapotranspiration is fairly high.

Figure 7 illustrates the plot layout and the location of the weather station and soil moisture sampling points.

4.1.1. Instrumentation

Precipitation: A 15 cm Belfort weighing type recording rain gage was used to measure the water input to the plots. The rainfall is recorded with a pen trace on a clock driven cylindrical drum chart. The chart made one revolution every 48 hours yielding a time resolution of approximately ± 5 minutes and a depth resolution of ± 0.025 cm.

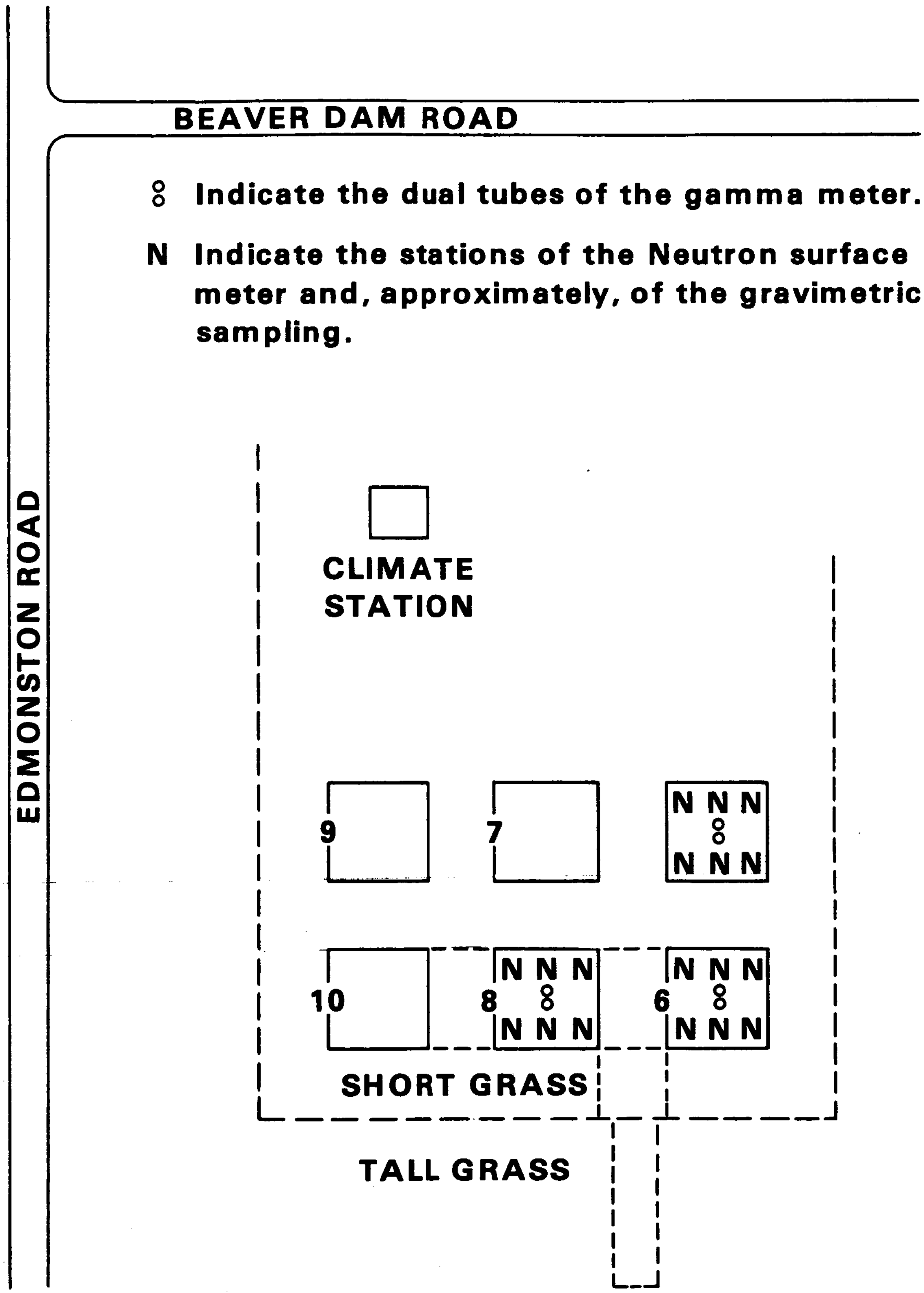

Figure 7. Location Designations Used by USDA, Hydrology Lab.

Evaporation: A class A evaporation pan was used to measure daily evaporation. Water loss or additions (during rain periods) were measured each day at about the same time, approximately 9:00 a.m. The net loss was recorded as evaporation to ± .0025 cm.

Wind: A totalizing anemometer was installed 15 cm above the rim of the evaporation pan. This instrument recorded the total miles of wind movement since the previous reading.

Max-min Temperature-air: A V-shaped maximum, minimum theromometer was installed in the Class A instrument shelter to record the previous days high and low air temperature.

Max-min Temperature-water: A V-shaped maximum-minimum thermometer was installed in the bottom of the evaporation pair to record the previous days high and low water temperature.

Air Temperature and Relative Humidity: A recording hygrothermograph was installed in the Class A instrument shelter to continously record air temperature and relative humidity.

Soil Moisture: Several methods were used to measure soil moisture including:

Two Probe Gamma Meter: A Troxler 2376 two probe density gauge was used for detailed determination of the soil moisture profile. This instrument incorporates a 5 millocurie Cesium-137 source in one probe and a scintillation detector in the other probe. The probes are lowered in parallel aluminum access tubes approximately 30 cm apart. The intensity of the radiation received at the detector probe is directly proportional to the density of the material between the access tubes. In the field soil the density will remain constant except for changes in water content. Thus the changes in measured density can be used as direct measures of soil moisture.

The Cesium 137 produces gamma radiation of 662 Kev energy. By using a relatively small scientilation crystal, in the counting probe, the volume formed by the geometry of the crystal and the Cesium source approximates a pyramid with a rectangular base (1.2 X 2.5 cm) and a height of 30 cm. A photomultiplier tube produces pulses proportional to the gamma energy striking the scintillation crystal. A pulse-height analyzer selects only energy corresponding to the 662 Kev photons. These specific energy pulses are counted, their count rate being proportional to the density of the material defined by the pyramid between the two probes. Because of the instrument geometry, one is able to make profile density measurements with a spatial resolution of about one centimeter. The control rods for the 2-probes are set so that one can measure a soil moisture profile at 2.54 cm intervals.

Soil Moisture Measurement by Neutron Meter

All neutron meters work in the same way regardless of their source or counting arrangement. A neutron probe contains a radiation source which produces fast neutrons, and a detector which is sensitive only to slow neutrons. The detector creates an electrical pulse for each neutron it detects. As fast neutrons are emitted from the source within the probe, they move out through whatever substance is in the immediate surrounding vicinity; they are scattered, and a portion of them are reflected back into the detector portion of the probe. During their travel through the surrounding substance, the neutrons are slowed by the physical characteristics of the substance or medium. The quantity of them which become "slow neutrons" depends primarily upon the presence of Hydrogen atoms in the medium. With a known rate of emitting fast neutrons, the number of slow neutrons detected per unit of time can be related to the concentration of hydrogen. Since the chemical content of most soils is such that the primary hydrogen present is in the form of soil water, the rate of slow neutrons detected can be directly related to soil moisture.

Neutron meters have limited spatial resolution. The sphere of influence of the probe is the effective volume of soil in which the measurement is made. It is defined as the spherical volume which encloses 95% of all thermalized neutrons generated by the source. Practically speaking the sphere of influence is a sphere about 30 cm in diameter. Also this volume is not a constant but increases as soil moisture decreases and vice versa.

Neutron Surface Moisture Gauge:

A Troxler Model 217 Surface Moisture Gauge, with scaler, was used for making measurements of soil moisture in the top 10-15 cm.

The average volume of measurement is a hemisphere approximàtely 15 cm. in radius. As the moisture content increases the zone of measurement decreases. Thus the meter determines the average soil moisture for the upper 10 to 15 cm. but cannot determine layers or gradients of soil moisture.

The surface probe is a self contained unit consisting of a 50 mc Americium -241, Berillium source, counting tube and pre-amp. An external counter connected by cable to the probe is used to determine the count rate.

Neutron Depth Moisture Gauge

A Nuclear Charge P-19 depth probe was also available but not used to measure soil moisture. The P-19 probe uses a 5 mc Radium-Berillium source. To make a measurement the single probe, containing the source counting tube and pre-amp, is lowered into an access tube to the desired depth. Measurements closer than 15 cm to the top are not valid because the sphere of influence intersects the surface. The result is a loss in neutrons and a reading that is generally too low. Because the effective measurement volume is about a 30 cm sphere, the neutron probe is not good for precise profile measurements. However, used carefully, the instrument can give a good measurement of total water content in a profile and is very good for monitoring soil moisture changes.

Calibration:

Each of the nuclear soil moisture gages comes with a factory calibration curve. However this curve must be verified for the particular site and soil. For these experiments, each of the instruments was calibrated by destructive sampling after the microwave data collection period was completed. Measurements were taken during a relatively dry and relatively wet period. These data established the calibration lives which are linear for the neutron meters and linear on a semi-log plot for the gamma density probe.

Field Measurement Program

Precipitation and pan evaporation were determined on a daily basis. Soil moisture was measured at least twice a week and every time microwave measurements were made by NASA. Table 4-1 summarizes the soil moisture sampling for each plot.

Table 4-1
Soil moisture measurement program for each plot

	Number Sample Sites	Depth
Gravimetric	6	0-2.5
		2.5-5
		5-15
Surface neutron	6	0-15
Two probe gamma	1	*
		3.8
		8.9
		14.0
		19.1
		24.1
		29.2
		34.3
		39.4
		47.0
		54.6
		62.2
		77.7
		92.7
		100.0

*These are the depths at which the source center was located. The effectively measured layer is from 1 cm above to 1 cm below the center; i.e. 1½ inch measures from 1 to 2 inches.

4.1.2. Field and Laboratory Procedures

(a) Gravimetric:

At each of the six sites on each plot (approximate locations show in Figure 7), a sample of approximately 300 grams was taken for each of the three depths. The samples were carved from the face of a shallow hole with a 5 X 10 cm spatula. The sample was labeled and immediately sealed in a plastic oven bag or an aluminum soil sample can.

The samples were taken into the lab and weighed (wet weight) that same day. The samples were then oven dried at 105°C for 24 hours. The samples were weighed again (dry weight) and the weight of the container was recorded. These three weights were punched on cards with the proper date and plot identification information for computer calculation of soil moisture. Volumetric soil moisture is calculated by the following:

$$\theta v = \left(\frac{\text{wet weight} - \text{container weight}}{\text{dry weight} - \text{container weight}} - 1\right) D_b \tag{18}$$

where D_b is the bulk density.

(b) Surface soil moisture – neutron meter

At each of six marked points in each plot, two, one-minute counts were made to measure the surface six inch (approximately) soil moisture. These counts were used, with shield counts before and after the series of plot measurements, as input data to the computer program. The program determined the count ration (CR) by the following:

$$CR = \frac{\text{avg counts/min at sample site}}{\text{avg counts/min with shield}} \tag{19}$$

Soil moisture was then determined by the following relationship

$$\%\ \text{Soil Moisture} = -68.9593 + 125.3604\ (CR) \tag{20}$$

where the coefficients of this linear equation were determined by a least squares fit of the calibration data.

(c) Profile Soil moisture with 2-probe gamma meter

Profile soil moisture was measured at one location in each plot with the 2-probe gamma meter. Two parallel aluminum access tubes were installed to a depth of approximately one m. each plot. Measurements were made by lowering the source and counting probe to the depths listed in Table 4-1 and recording the count rate over one minute. The count ratio was determined according to

$$CR = \frac{\text{counts/min at each depth}}{\text{counts/min for Magnesium standard}} \tag{21}$$

The wet density (D_{bw}) is then determined directly from the count ratio with the following relationship

$$CR = a\, e^{-b\ Dbw} \tag{22}$$

where a and b are instrument constants;

$$a = 18.89795 \text{ and } b = 0.027009$$

After solving for D_{bw}, the volumetric soil moisture θv is calculated from

$$\theta v = (D_{bw} - D_b)\ 100 \tag{23}$$

(d) Bulk density from two probe gamma meter

Bulk density (D_b) can be measured directly with the two probe gamma meter. This instrument gives us the capability to determine D_b by layer. The general procedure used was to measure the wet bulk density (D_{bw}) with the two probe gamma meter. The measured layer was then removed and its moisture content determined gravimetrically. This sampling was done after all measurements had been made on the plots and they could be "destroyed." Bulk density was then calculated by:

$$D_b = D_{bw} \Big/ \left(1 + \frac{\theta w}{100}\right) \tag{24}$$

where θw is the percent moisture on a dry weight basis

4.1.3 Field Data and Results

Obtaining detailed soil moisture data in the surface 10 cm layer was difficult because the bulk density changed rapidly with depth and was not constant from plot to plot. Bulk density values were calculated from the gravimetric and corresponding gamma meter data. There were only two sampling depths for these two types of data. These are shown in Table 4–2 below.

The moisture contents of all four gravimetric sampling depths were computed using these bulk density values. The moisture contents of only the top three gamma meter depths were so computed.

Table 4–2
Computed bulk density values.

Density (cm)	gravimeter	2.54 – 5.08	5.08 – 10.16
	gamma meter	3.8	8.9
Density (g/cm^3)	plot 8	1.328	1.562
	plot 5	1.607	1.635
	plot 6	1.474	1.444

At greater depths they were computed with an estimated bulk density value of 1.65. The soil moisture data acquired by these procedures are given in Appendix A.

4.2 Biomass Data:

Since planting was done with conventional mechanized seed planters, the spacing of plants within the row was not equal. During the growing season, plants with more space tended to develop a larger biomass than those which were cramped for space. Thus sampling was accomplished by cutting 1.52 linear meters of row in the border areas adjacent to the foot-print of the microwave radiometer. These samples contained 5 to 9 plants in the corn plots and 10 to 14 plants in the soybean plots. Plots were harvested and the total above ground vegetation was weighed for biomass determination. Biomass per plant was calculated from these samples for the corn and soybeans for six dates at approximately weekly intervals. The orchardgrass was sampled by clipping 1 square meter areas. The wet biomass was oven-dried to 0% moisture to determine dry biomass. Wet and dry biomass plus total water contained in the above ground vegetation were calculated for the unit area covered by the footprint of the radiometer.

Since the crops were physiologically mature, there was less variance in total dry biomass on a per plant basis than there was in total wet biomass of the samples during the period the radiometric measurements were taken. The biomass data obtained during the measurement program is tabulated in Appendix B.

5. Radiometer Data Recording and Processing

5.1. Real-Time Processing

The need for the real-time data processing is threefold. First, the normal functioning of the sensor systems could be monitored. Secondly, if there is a RFI (radio-frequency interference) problem, the real-time printout could give the clue immediately. Thirdly, quality of the data provided by the real-time printout aided the planning of the next measurements. It was from a study of the real-time data output that we were able to detect an open circuit in the C-band cold load before the field measurements began. During the field measurements, with the aid of the real-time data we were able to detect a L-band RFI signal at incident angles of 50°-60° when the antennas were scanning towards the southeast direction of the test site. The measurements were repeated immediately and the RFI signal was persistent.

The real-time data processing program was written in Simple Basic language. Figure 8 shows the block diagram of the program flow. Most of the elements in the diagram are self-explanatory. However, a few of them need to be clarified further. The housekeeping data taken during the measurements includes date, time of the measurements, incident angle of the sensors, the antenna line temperatures, hot and cold load line temperatures for both L- and C-band radiometers. Some of these parameters were displayed during the data printout immediately after the radiometric measurements. As far as the data processing is concerned, there were two major modes of operation, namely, the normal operational mode and the system calibration mode. In the normal operational mode, the radiometric measurements at L- and C-band frequencies were made sequentially. In each measurement cycle the voltages of cold and hot reference loads as well as the target antenna responses in both polarizations for a given radiometer the sampling frequency was specified by the operator (normally 50 samples at each load position). After the measurement cycle was complete, the average normalized voltages for both polarizations were computed according to Eq. (7). The standard deviations of the normalized voltages were

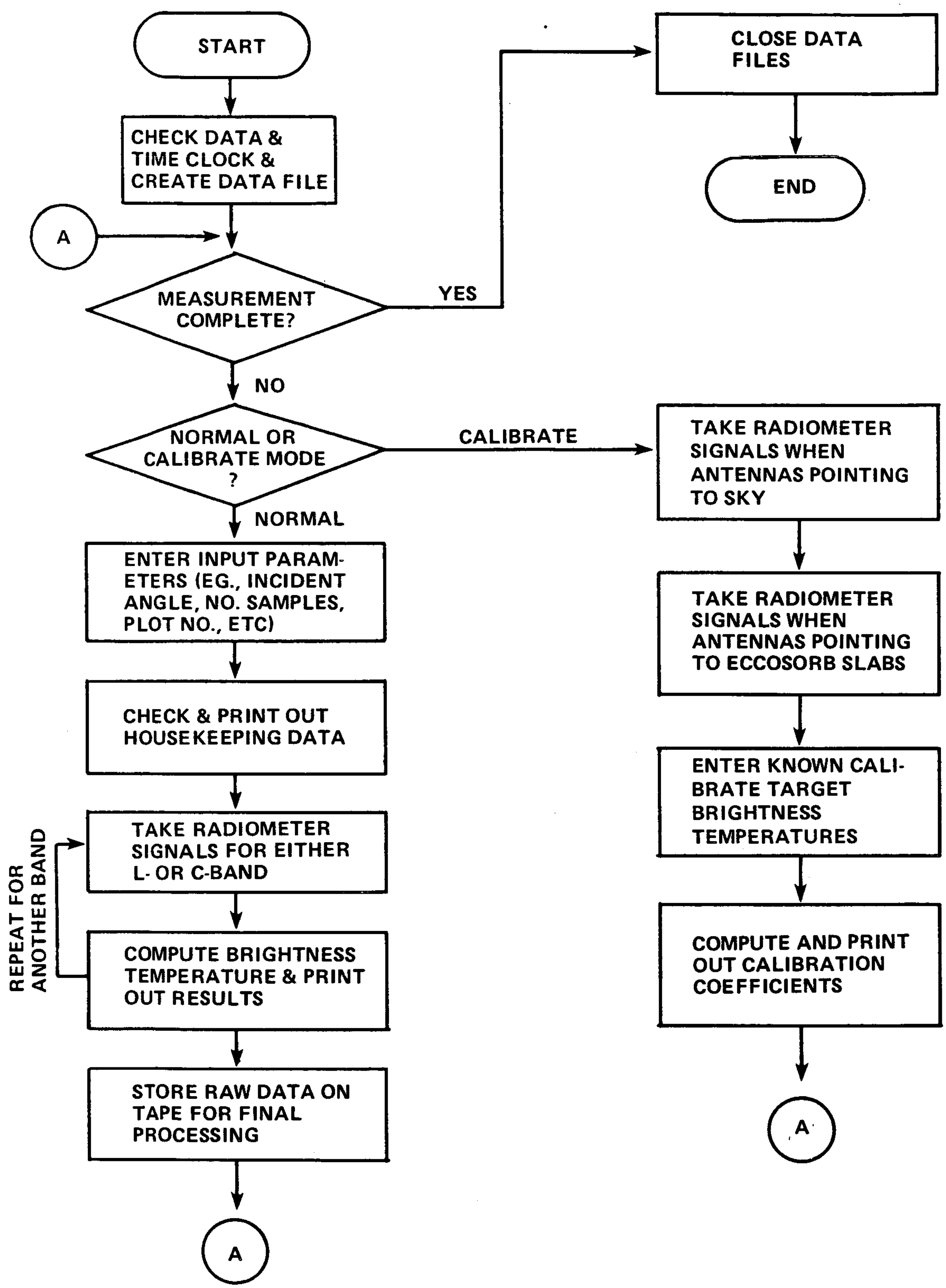

Figure 8. Flow Chart of the Real-Time Data Processing Program.

also estimated according to the standard statistical formulas. The conversion to target brightness temperatures were immediately made with Eq. (12) and the results printed out together with appropriate housekeeping data. The same measurement cycle was repeated for the other radiometer. At the completion of these measurement cycles, the radiometric data, the housekeeping data as well as the information on date, time and field type were recorded on tape. The next measurement sequence at another incident angle followed the same procedure.

There were two different operational sequences in the system calibration mode. The first one was the same as that for the normal operational mode. The brightness temperatures of the calibration targets (Eccosorb slab, sky, and water) were derived using the existing conversion coefficients. In the second sequence, a new set of the conversion coefficients was derived using the newly measured data set. The known target brightness temperatures would have to be entered in the program. This particular sequence of operation was very seldom employed.

5.2. Final Data Processing

After the measurement program was completed at the end of October, 1979, all the data recorded on magnetic tapes were processed by the same HP 9835 Desktop calculator using the refined version of the conversion coefficients. This new set of conversion coefficients was derived by combining all the calibration data together. The brightness temperature of the Eccosorb slab was about equal to its physical temperature and was measured during calibration. The sky brightness temperatures in clear conditions were calculated to be 5.0°K and 5.2°K at L- and C-band frequencies respectively. The brightness temperature of water depends on incident angle and polarization and could be calculated rather accurately knowing its physical temperature. The results of the system calibration were already shown in Figures 3 and 4 for L-band and C-band radiometers respectively. A linear regression analysis was applied to each of four data sets (two polarizations and two frequencies) and the results giving the relation between the brightness temperatures T_B's and the normalized antenna voltages N's are:

for L-band

$$T_{BV} = -265.33\, N_V + 336.88 \tag{25}$$

$$T_{BH} = -339.84\, N_H + 339.22 \tag{26}$$

and for C-band

$$T_{BV} = -363.08\, N_V + 417.58 \tag{27}$$

$$T_{BH} = -305.10\, N_H + 375.92 \tag{28}$$

where the subscripts V or H in both T_B and N stands for the vertical or horizontal polarization. The correlation coefficient of the regression for each data set is ≅ 1. An analysis on the deviations of the data points from the regression lines shown in the figures gives the accuracy of the radiometric measurements of about ± 3°K. This same estimate of accuracy is also applicable to the normal radiometric measurements over the bare and vegetated fields, barring any serious instrumental problems.

All the radiometric measurements over bare and vegetated fields were processed according to Equations (25) through (28) to obtain the brightness temperatures from the measured normalized antenna voltages. The results are given in Appendix A together with the soil moisture and temperature ground truth taken concurrently with the radiometric measurements. The standard deviation associated with each brightness temperature value listed in the appendix is based on the statistics of 50 samples each of the antenna, cold, and hot load voltages. The measured brightness temperatures at nadir incidence are of questionable quality because of the contribution from the radiometer self-emission scattered back from the ground surface, as discussed in Section 2. Those measured T_B's (in Appendix A) marked with an asterisk are subject to the RFI noise.

6. Typical Measurement Results.

a. Bare Field Results

Figure 9 shows the plot of vertically and horizontally polarized brightness temperatures, T_{BV} and T_{BH}, for both C- and L-band radiometers against the incident angle θ for a bare wet

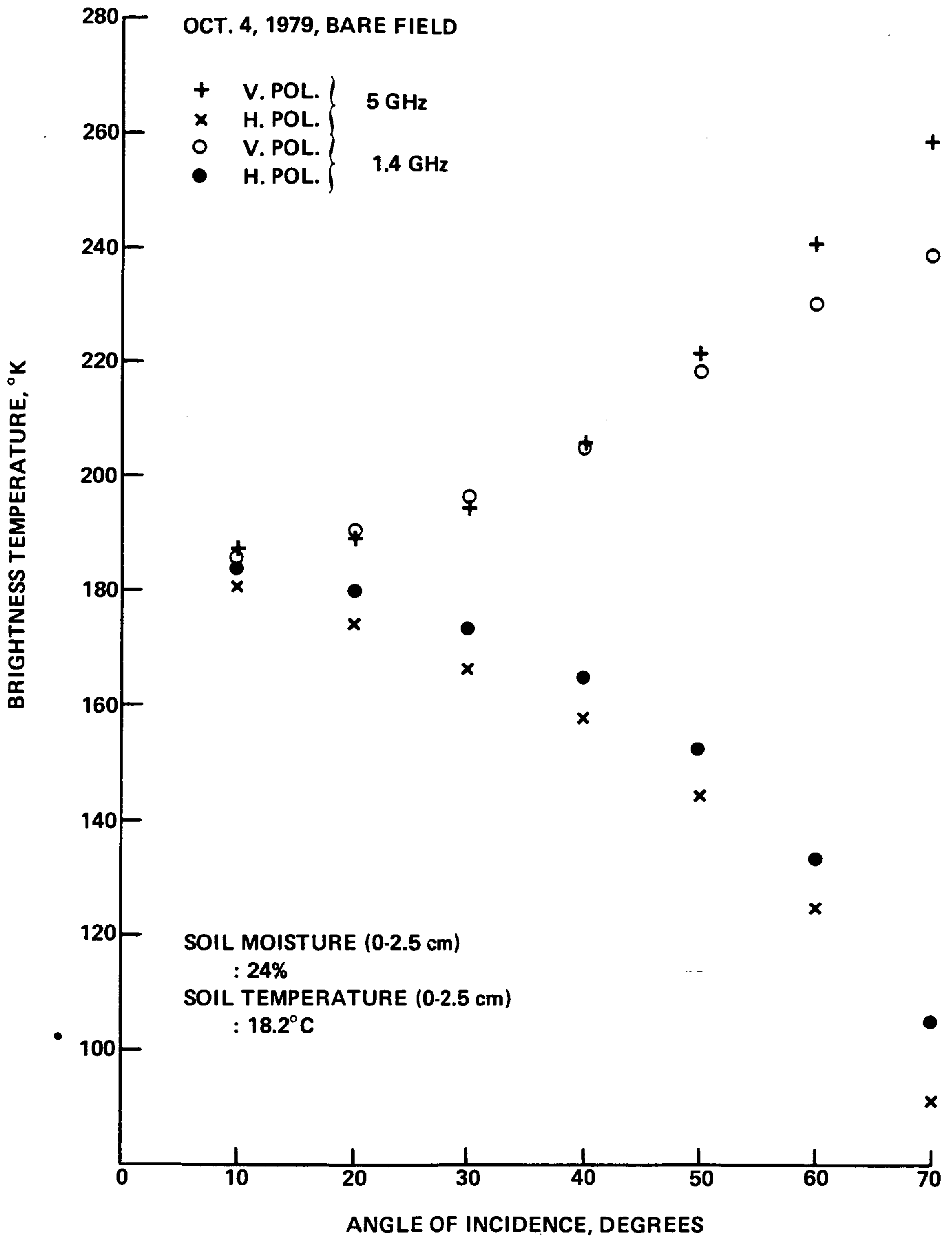

Figure 9. The Measured C- and L-Band Brightness Temperatures Plotted Against the Angle of Incidence for a Bare Field. The Soil Moisture Content at Top 2.5 cm Layer was ~24% by Dry Weight.

field. The measurements were made on Oct 4, 1979. The soil moisture content W and soil temperature T_S at the top 0-2.5 cm layer are also indicated in the figure. A similar plot of data obtained on Oct 23, 1979 for a typically dry field condition is shown in Figure 10. Both figures show the general dependence of T_{BV} and T_{BH} on θ observed in the past (Njoku and Kong, 1977; Newton, 1977; Schmugge, 1980). When the field is wet, both T_{BV} and T_{BH} are low ($\sim$ 185°K) at $\theta \leqslant 10°$ and T_{BV} increases and T_{BH} decreases rapidly with increasing θ. The Brewster's angle is well beyond $\theta = 70°$. When the field is dry, both T_{BV} and T_{BH} at $\theta \leqslant 10°$ are $\simeq$ 250°K for L-band measurement and $\simeq$ 260°K for C-band measurement. T_{BV} increases with θ much more slowly compared to the case of wet field, and the Brewster's angle occurs around $\theta \simeq 50°$-$60°$. There is only $\sim$ 4°C difference in the soil thermal temperatures between the dry and wet field conditions. But the corresponding difference in the brightness temperatures is about 70°K at $\theta \leqslant 10°$, showing the dominant factor of soil moisture content.

The L-band horizontally polarized brightness temperatures at $\theta = 10°$ are plotted as a function of moisture content in the top 2.5 cm layer in Figure 11. The similar plot for C-band is given in Figure 12. All the observed brightness temperatures are normalized to the soil thermal temperatures to minimize the effect of thermal temperature variations. For both L- and C-band results, the normalized T_B's are observed to decrease with increase in soil moisture content as expected. A regression analysis of these data gives correlation coefficients of 0.89 for L-band and 0.84 for C-band. Note that a steeper slope is obtained for the C-band data set compared to that for L-band. This is caused by the fact that, for moisture content W > 10%, the measured C-band T_B's are lower compared to the corresponding L-band T_B's in most occasions. A more direct comparison of the C-band and L-band measurement results at O = 10° is given in Figure 13. Both vertically and horizontally polarized data are entered in the figure. It is clear that most data points fall below the 1:1 line, indicating lower C-band brightness temperature.

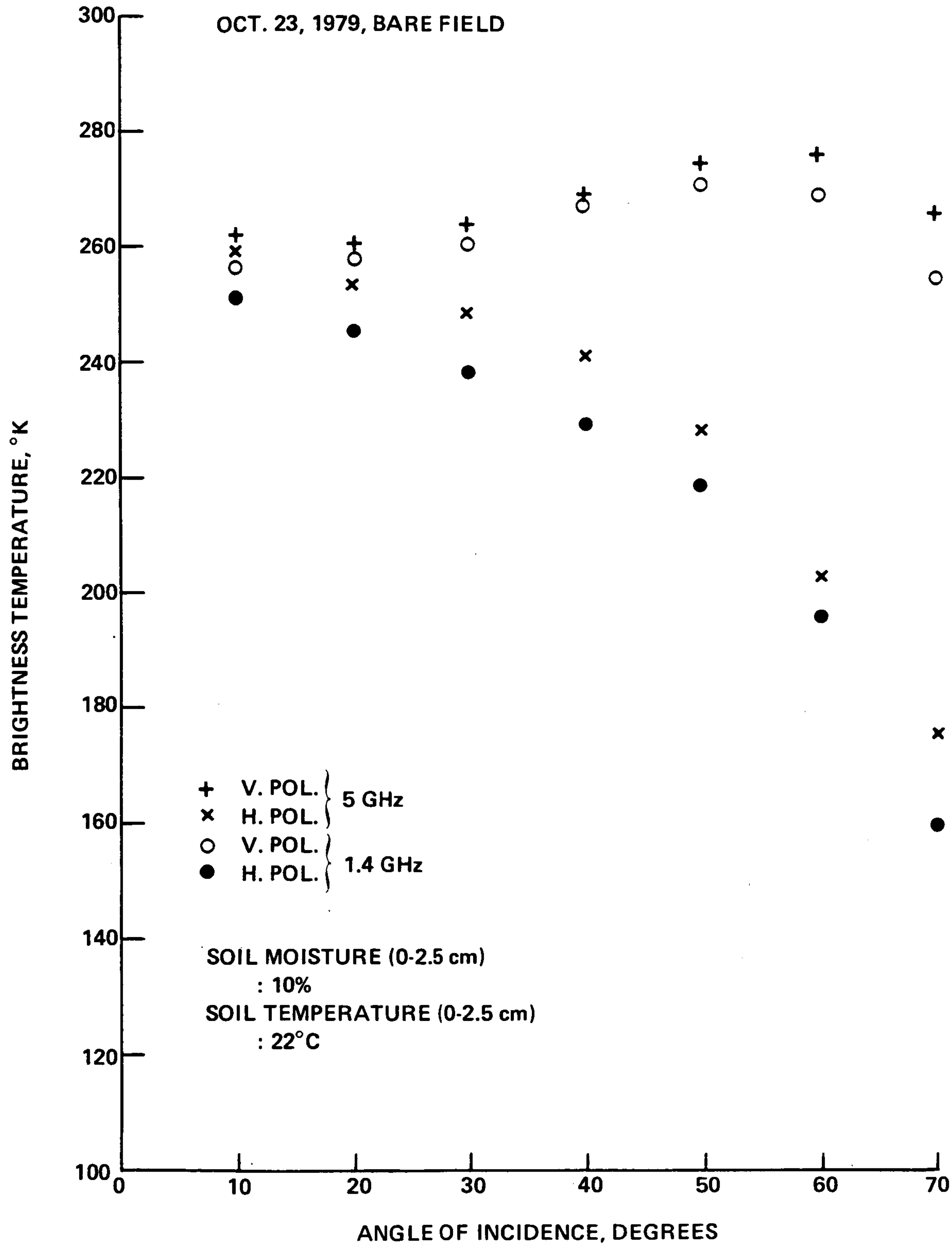

Figure 10. The Measured C- and L-Band Brightness Temperatures Plotted Against the Incident Angle for a Bare Field. The Soil Moisture Content at Top 2.5 cm Layer was ~10% by Dry Weight.

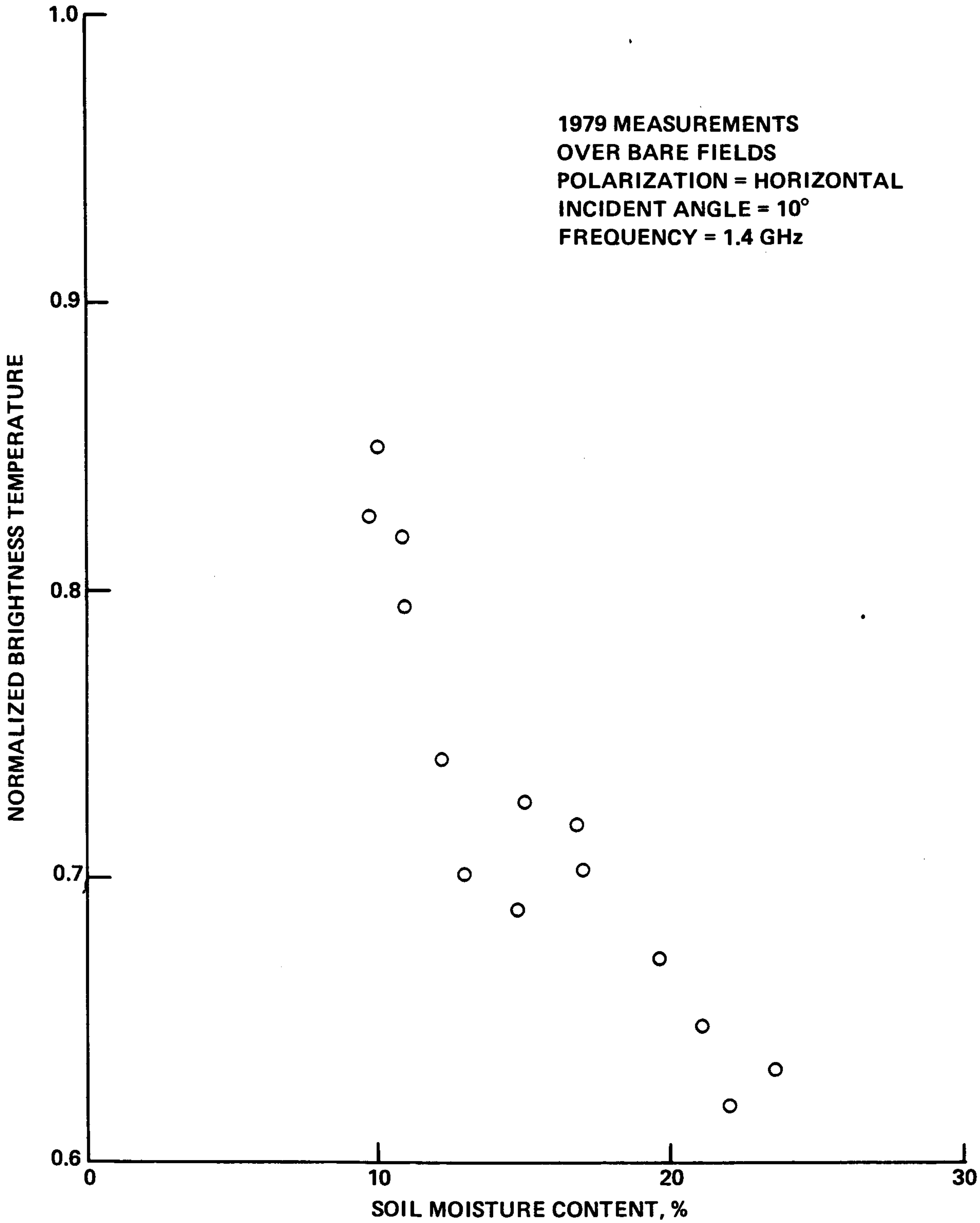

Figure 11. The Normalized Brightness Temperature at L-Band Plotted as a Function of Soil Moisture Content in the Top 2.5 cm Layer.

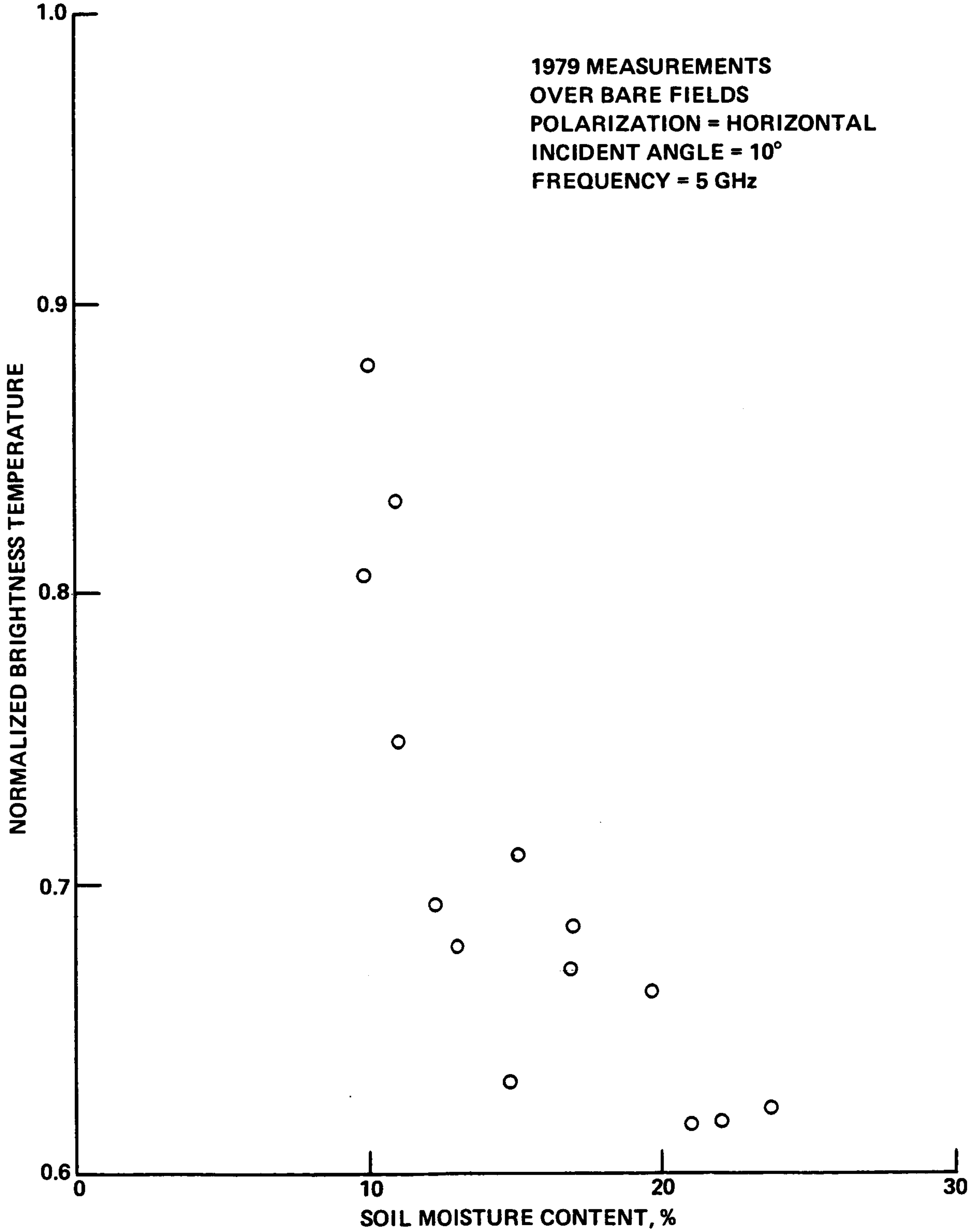

Figure 12. The Normalized Brightness Temperature at C-Band Plotted as a Function of Soil Moisture Content in the Top 2.5 cm Layer.

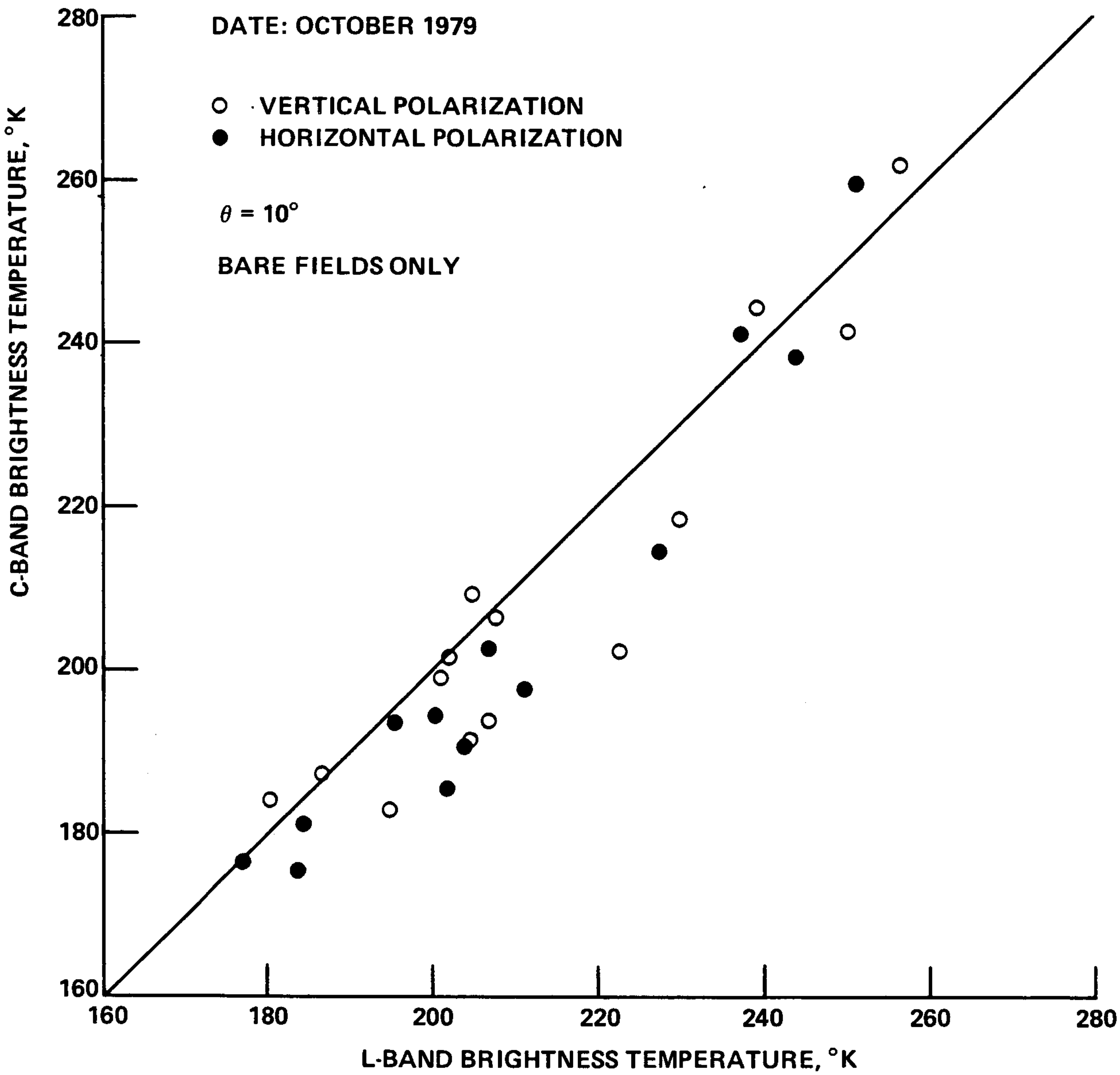

Figure 13. A Comparison of the Measured C- and L-Band Brightness Temperatures Over Bare Fields at 10° Incident Angle.

The reason for the observed low C-band brightness temperature is not clear. A possible explanation comes from the fact that the C-band antenna has a significant side lobe located at $\sim 80°$ away from the main beam as discussed in Section 2. When the measurements at $\theta \geqslant 10°$ were made, this side lobe pointed to the sky and observed the brightness temperature of $\sim 5°K$. Estimation of this contribution is difficult because only a single-cut antenna radiation pattern measurement was available.

b. Vegetated Field Results

Fields with three types of vegetation cover (corn, soybean, and grass) as described previously were included in the radiometric measurements. Figure 14 showed the measured results on October 15, 1979 for the corn field with radiometers scanning parallel to the row direction. Results of measurements on the same day with radiometers scanning perpendicular to row direction were shown in Figure 15. As the measurements were made late in the growth season, the corn was already wilted and a good portion of soil surface was exposed to the sensors. As a result, there is a definite dependence of the measured brightness temperature T_B's on the row direction of corn. For measurements parallel to the row direction, the L-band Brewster's angle occurs at $\theta \simeq 60°$. For measurements perpendicular to the row direction, the Brewster's angle changes to $\theta \simeq 40°$. The C-band result did not show the Brewster angle effect for $\theta \leqslant 70°$ regardless of the sensor's look directions. However, the C-band horizontally polarized brightness temperature T_{BH} began to increase with θ when $\theta \geqslant 40°$, for measurements perpendicular to row direction. The C-band T_{BH} increase with θ was not observed until $\theta \simeq 70°$ for measurements parallel to row direction. The lower T_B's for C-band than those for L-band at $\theta \leqslant 30°$ could be partially due to the C-band antenna problem discussed previously. Another possible reason might be due to the fact that C-band antenna has smaller beamwidth than the L-band antenna. At small θ, a comparatively large fraction of scene brightness might come from bare soil within the C-band footprints.

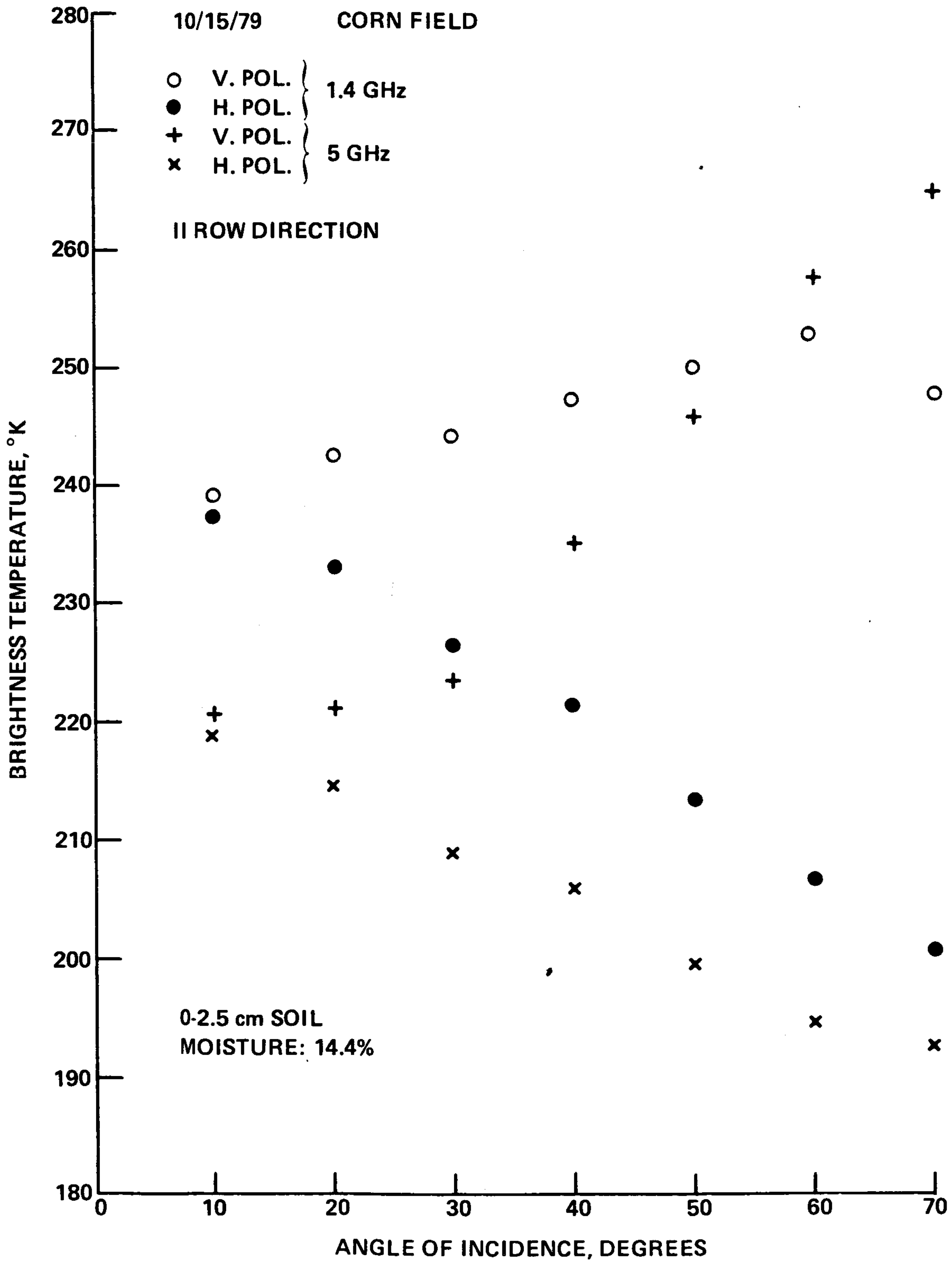

Figure 14. The Measured Brightness Temperatures Plotted Against the Incident Angle O for a Corn Field. The Direction of Radiometer Scan was Parallel to Row Direction.

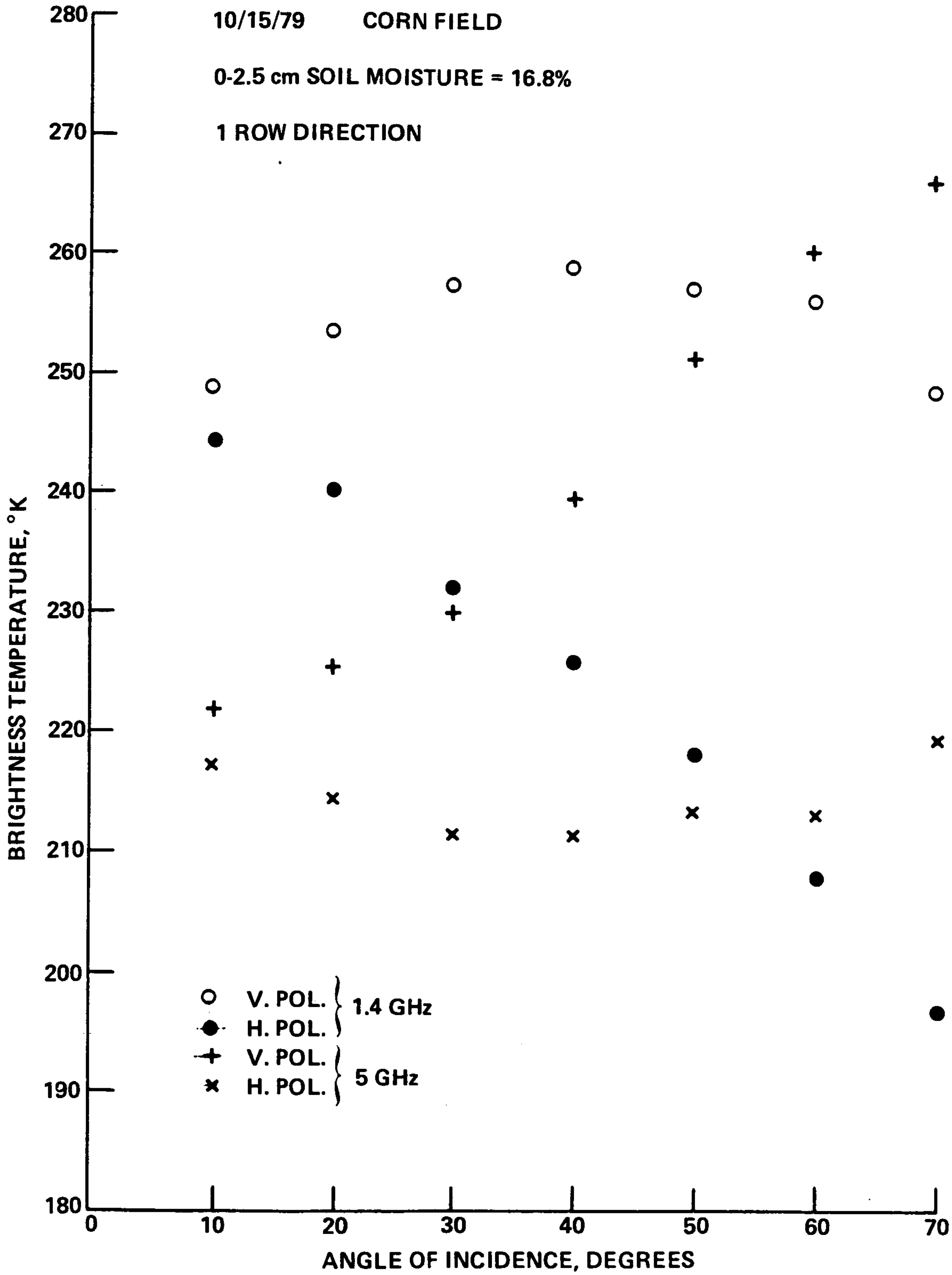

Figure 15. The Measured Brightness Temperatures Plotted as a Function of Incident Angle for a Corn Field. The Direction of the Radiometer Scan was Perpendicular to Row Direction.

The results of a typical measurement over the soybean field were shown in Figure 16. Unlike the corn which grows straight up, the soybeans grow more irregularly. As a result, the field covered with the fully grown soybeans shows little effect of row direction in the radiometric responses at both C-band and L-band frequencies. It is clear from Figure 16 that C-band T_B's in vertical (T_{BV}) and horizontal (T_{BH}) polarizations show very little differences, suggesting an almost total shielding of emission from soil. The L-band measurements gave lower T_B's than those of C-band and T_{BV} and T_{BH} were different, indicating less shielding effect of emission from soil surface. However, when comparing the results of bare field and soybean field measurements, the effect of vegetation cover is significant. For example, a bare field with approximately same soil moisture and temperature profiles gives a measured T_B of $\simeq$ 195°K at $\theta = 10°$ as shown in the figure, as compared to $T_B \simeq$ 240°K at the same θ for the soybean field.

The radiometric responses for the types of grasslands taken on Oct. 16 were shown in Figures 17 and 18. The canopy and soil temperatures for both grasslands were comparable. The soil moisture content in the top 2.5 cm layer for the 30 cm tall grassland was 24%, while that for the 10 cm grassland was 19%. The measured T_B's at $\theta = 10°$ for the 10 cm grassland were ~ 255°K and ~ 210°K at C- and L-bands respectively. The similar measurements over the 30 cm grassland gave ~ 265°K and ~ 220°K respectively at C- and L-bands. Comparisons with the bare field results suggest that, without the grass canopy, the same fields should have T_B's of ~ 180°K and ~ 192°K at $\theta = 10°$ for both C- and L-bands for moisture contents of ~ 24% and ~ 19% respectively. The estimated increases in T_B's at L-band due to presence of the 10 cm and 30 cm grass covers were, therefore, ~ 18°K and ~ 40°K respectively. The corresponding increases in C-band T_B's were ~ 63°K and ~ 73°K respectively for the 10 cm and 30 cm grasslands. Since the brightness temperatures for bare and vegetated fields are expected to be close at very small soil moisture content, a linear regression between brightness temperature and soil moisture content would give a smaller slope for the vegetated fields than for the bare fields. This suggests that the

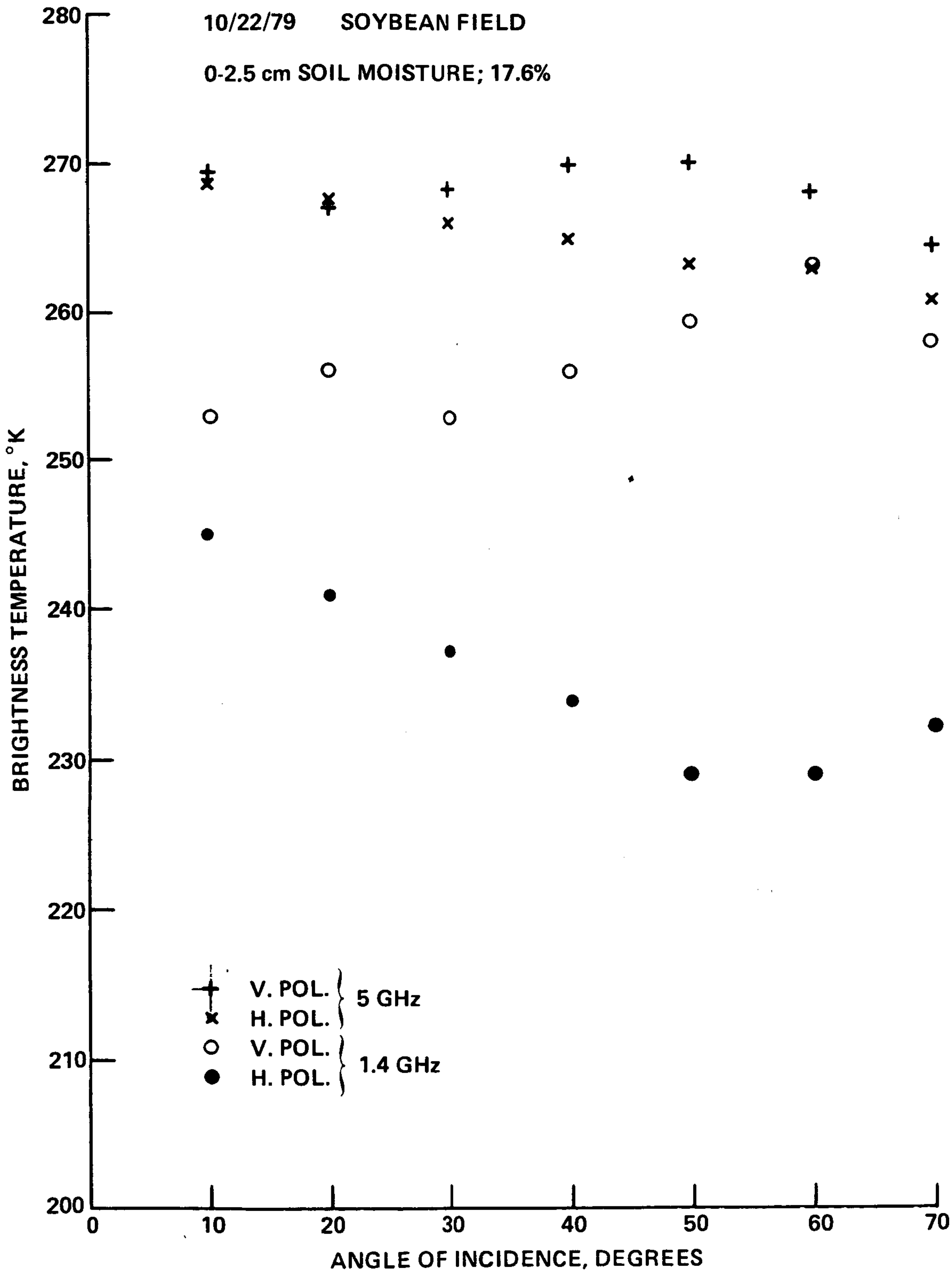

Figure 16. The Measured Brightness Temperatures Plotted Against Incident Angle O for a Field Covered with Soybeans.

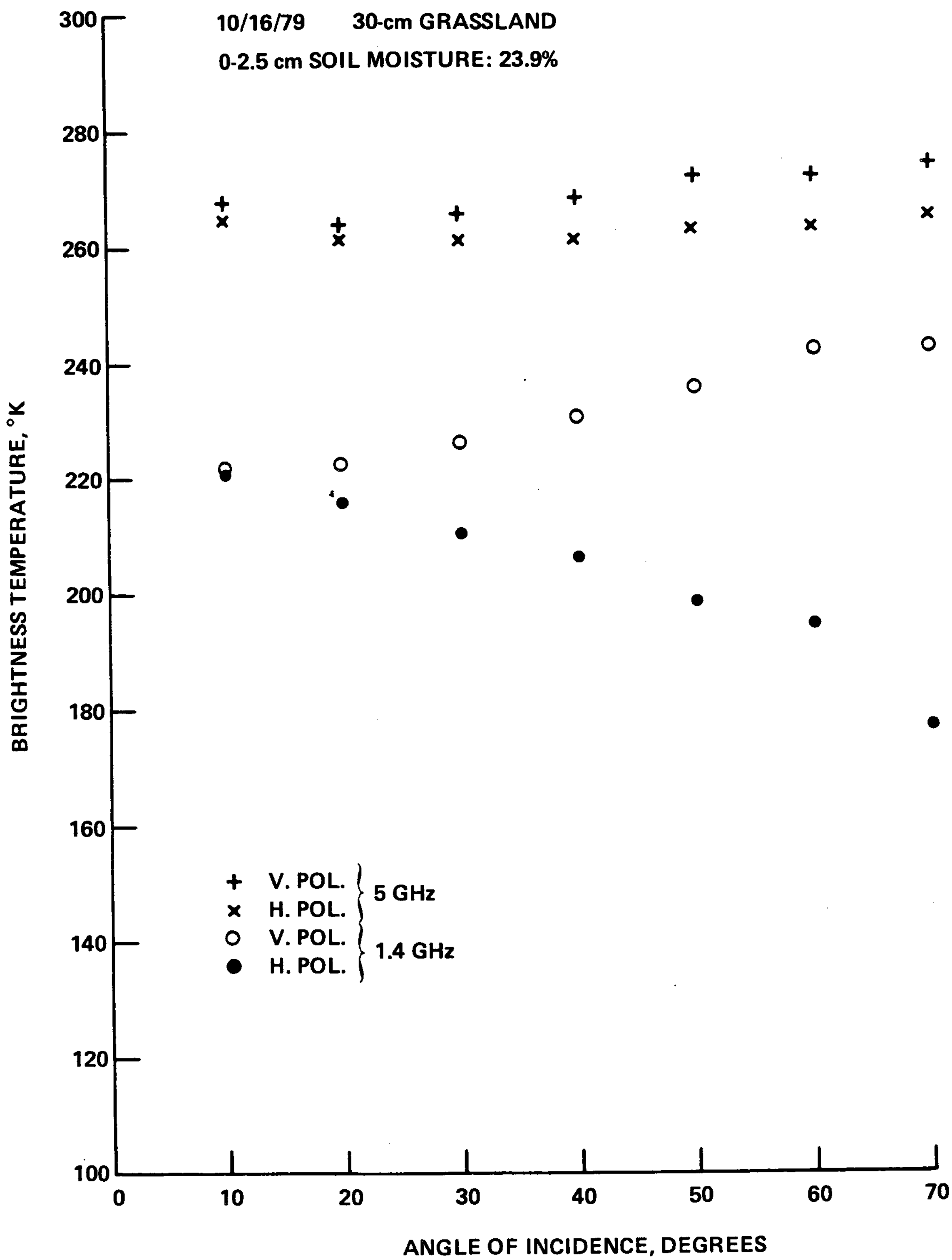

Figure 17. The Measured Brightness Temperatures Plotted Against Incident Angle O for a Field Covered with 30 cm Tall Grass.

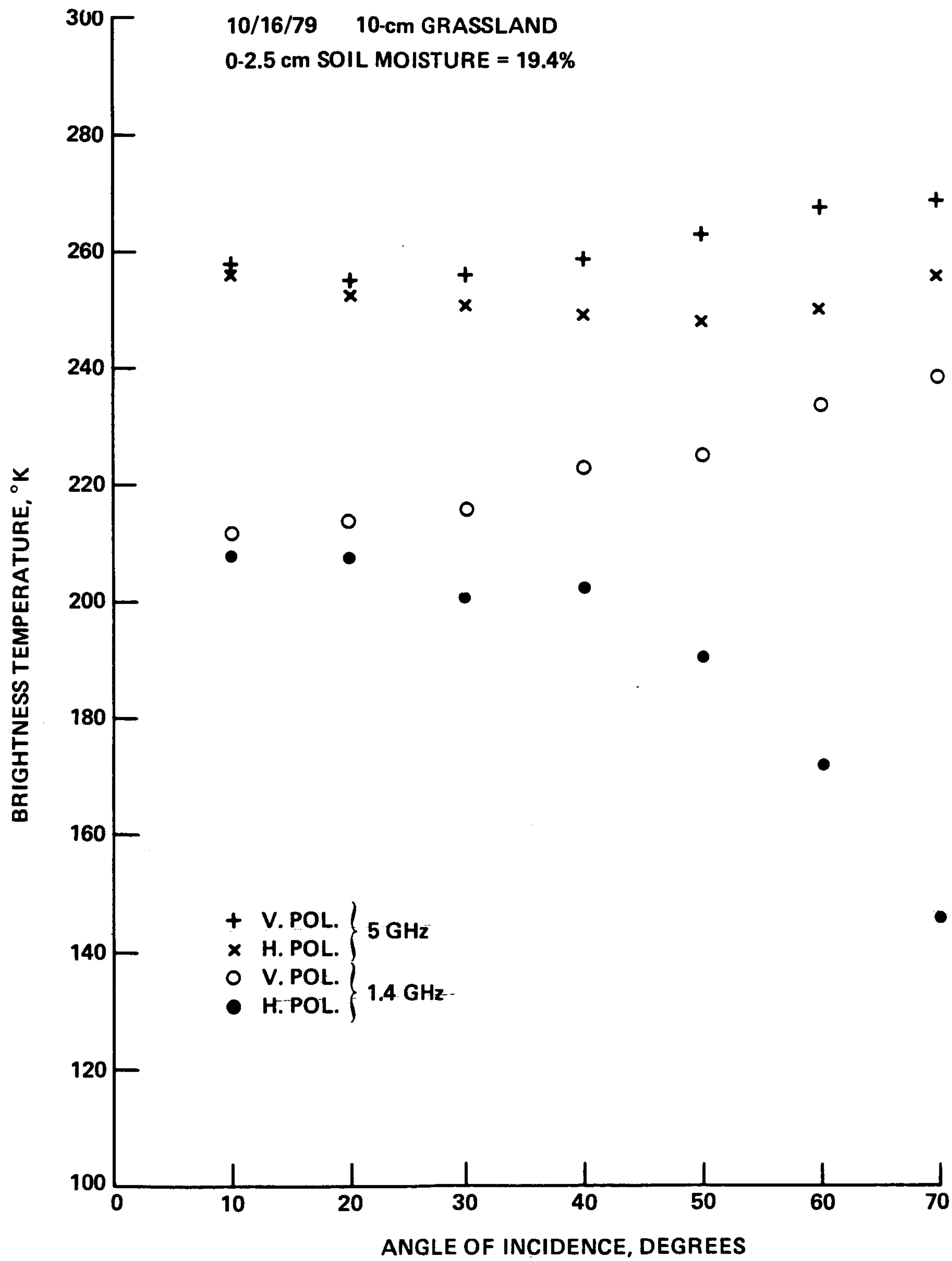

Figure 18. The Measured Brightness Temperature Plotted Against Incident Angle O for a Field Covered with 10 cm Tall Grass.

sensitivity of soil moisture remote sensing by microwave radiometers is reduced under the presentation of the vegetation cover.

7. Summary

The remote measurements of soil moisture content reported here marked the beginning of the extensive research program jointly undertaken by NASA/GSFC and USDA/BARC. Because of the acquisition and installation of the data processing system and the malfunction of the C-band radiometer, the field measurements were delayed until early October when the soybean were fully grown and the corns already wilted. Consequently, the field operation and data collection covered only over 1-month period. Although the data set was not as extensive as we originally planned to acquire, the preliminary analysis given in the previous sections did show some new results. First, the absolute accuracy of the measured L-band brightness temperatures based on the calibration results of known targets (sky, water, and Eccosorb) is about ± 3°K. The measurements are valid over wide incident angle range of 10°-70°. The measured C-band brightness temperatures could have an approximately constant bias over the same range of incident angles because of the postulated antenna side lobe problem. However, if the effect of vegetation cover is assessed with respect to a bare field, then the C–band measurement results are valid in this regard. Secondly, the presence of vegetation cover reduces the sensitivity of soil mositure remote sensing capability at both L–and C–bands. Comparisons of measurement between bare and vegetated fields show that the sensitivity reduction is more severe at C-band than at L-band, and appears to increase with the increase in the amount of vegetation cover.

Appendix A

Soil Moisture Data

Table A1.
Soil moisture content (%) measured by gamma meter for bare field, plot 8.

Date \ Depth (cm)	3.8	8.9	14.0	19.1	24.1	29.2	34.3	39.4	47.0	54.6
8/13/79	19.79	23.88	27.14	29.82	24.49	27.62				
8/14/79	18.04	23.81	26.75	29.63	25.74	31.45	32.51			
8/15/79	19.38	25.20	28.44	30.73	27.51	31.38	33.31	26.65		
8/16/79	20.53	23.02	27.27	28.47	23.98	29.37	34.20	26.48		
8/17/79	17.43	23.46	25.98	28.38	21.51	28.54	32.32	26.21		
8/27/79	18.91	23.48	25.97	29.23	23.82	28.88	31.06	24.46		
8/28/79	19.23	26.22	28.23	28.98	23.50	29.72	33.13	25.18		
9/11/79	17.46	25.37	26.75	28.92	24.80	30.97	33.70	29.35	29.33	34.03
9/17/79	18.87	24.12	25.29	27.60	21.55	29.22	30.75	27.75	25.95	29.50
9/20/79	16.19	20.89	23.35	24.92	21.14	28.11	30.79	25.37	26.73	31.85
9/24/79	22.82	27.72	29.82	31.28	26.08	29.55	33.38	29.61	28.70	34.38
9/27/79	17.97	26.97	25.27	26.87	24.38	26.93	30.83	25.75	26.23	35.10
10/17/79	22.13	26.26	28.15	33.78	29.37	30.37	35.27	31.67	30.54	37.26
11/ 2/79	18.19	21.67	24.09	26.76	20.02	27.61	30.56	25.57	23.49	29.68

Table A3.
Soil moisture content (%) measured by gamma meter for soybean field, plot 6.

Depth (cm) / Date	3.8	8.9	14.0	19.1	24.1	29.2	34.3	39.4	47.0	54.6
8/13/79	20.22	21.62	22.75	20.13	21.41	38.17	43.34			
8/14/79	24.84	21.55	26.64	20.34	23.70	44.20	47.33			
8/15/79	24.78	18.86	25.39	19.21	20.71	44.43	46.90	42.21		
8/16/79	24.43	19.69	23.14	18.93	22.76	44.14	48.54	42.36		
8/17/79	21.67	17.01	21.88	15.33	21.32	41.09	45.92	40.34		
8/27/79	22.07	18.95	20.85	14.37	19.44	41.01	42.99	38.15		
8/28/79	31.14	27.31	31.83	23.20	26.34	45.21	49.42	44.77		
9/12/79	28.04	22.83	26.48	23.61	25.39	46.27	51.42	41.87	39.49	43.62
9/18/79	23.89	18.72	24.18	18.47	21.99	43.00	48.63	39.01	33.40	36.97
9/27/79	24.05	23.10	27.05	19.34	24.32	44.56	47.29	42.39	38.33	43.74
10/ 2/79	32.24	30.59	34.67	25.34	28.78	46.23	49.27	42.53	41.03	46.90
11/ 2/79	26.74	24.61	25.36	21.97	24.15	44.83	49.44	38.32	36.18	39.98

Table A2.
Soil moisture content (%) measured by gamma meter for corn field, plot 5.

Depth (cm) / Date	3.8	8.9	14.0	19.1	24.1	29.2	34.3
8/15/79	14.40	18.73	9.78	6.74	14.72	10.73	
8/17/79	15.61	18.49	10.75	7.13	16.70	9.57	
8/27/79	16.64	18.42	9.66	5.63	15.47	7.68	
8/28/79	21.19	22.00	11.78	8.33	18.79	12.19	
9/13/79	18.88	21.23	14.36	9.34	20.52	15.12	8.02
9/18/79	16.56	19.19	11.90	8.11	18.58	11.95	2.91
9/27/79	18.63	19.54	15.99	9.56	20.14	12.45	3.92
10/ 2/79	22.43	24.14	17.76	10.47	21.71	16.45	7.65
10/31/79	20.24	24.93	20.84	15.48	20.85	13.03	7.99
11/ 2/79	17.43	19.34	14.03	9.29	19.37	12.34	9.60

Table A4.
Soil moisture content (%) measured by neutron surface motor for bare field, plot 8.

Date	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Plot Ave.
8/ 3/79	25.87	22.50	21.27	23.65	28.78	32.12	25.70
8/13/79	13.86	15.67	17.19	18.90	25.32	21.23	18.69
8/15/79	10.71	13.81	15.48	16.72	21.73	17.35	15.97
8/16/79	10.41	12.67	14.03	15.98	20.82	17.25	15.19
8/17/79	11.18	13.57	14.55	16.83	21.81	16.73	15.78
8/28/79	21.48	21.82	21.37	23.67	28.78	25.02	23.69
9/11/79	12.24	14.37	13.98	16.70	23.94	21.75	17.16
9/17/79	10.46	11.94	12.71	15.33	21.04	18.02	14.92
9/20/79	10.18	11.79	12.00	13.99	19.82	17.39	14.19
9/26/79	15.80	15.82	16.33	21.16	26.45	23.11	19.78
9/27/79	15.30	14.28	13.94	19.15	22.70	23.58	18.16
10/ 4/79	22.22	18.31	18.30	22.24	28.65	28.73	23.07
10/12/79	21.85	20.63	20.58	23.01	31.09	31.09	24.71
10/22/79	15.61	14.45	22.62	16.32	23.25	22.74	19.16
10/23/79	13.67	12.76	19.25	15.17	22.06	21.14	17.34

Table A5.
Soil moisture content (%) measured by neutron surface meter for corn field, plot 5.

Date	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Plot Ave.
8/ 3/79	22.03	22.04	22.12	21.35	18.11	17.23	20.48
8/15/79	14.06	17.25	16.07	15.95	14.14	15.79	15.54
8/16/79	12.82	15.54	14.07	14.48	12.77	14.94	14.10
8/17/79	12.86	15.50	14.03	13.93	12.14	14.84	13.88
8/28/79	23.88	23.58	23.32	23.14	21.66	23.58	23.19
9/13/79	15.03	17.73	17.37	16.43	14.50	15.91	16.16
9/18/79	13.46	15.74	16.57	15.26	12.41	14.43	14.65
9/26/79	19.90	20.29	20.51	19.58	17.96	18.63	19.48
9/27/79	19.48	20.78	20.32	19.20	17.76	19.35	19.48
10/23/79	19.73	20.36	20.19	17.86	16.56	17.86	18.76
10/31/79	16.81	20.38	18.31	18.52	20.67	18.76	18.91
11/23/79	15.68	18.79	18.39	16.23	19.13	17.92	17.69

Table A6.
Soil moisture content (%) measured by neutron surface meter for soybean field, plot 6.

Date	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Plot Ave.
8/3/79	21.42	20.01	22.01	22.79	25.09	24.22	22.59
8/13/79	24.71	25.20	22.43		26.73	25.97	
8/15/79	21.56	21.01	18.47	21.75	20.81	21.29	20.82
8/16/79	19.64	19.78	15.98	19.25	17.31	20.00	18.66
8/17/79	20.41	20.38	14.86	19.94	18.26	19.82	18.94
8/28/79	28.36	26.26	25.29	27.39	28.34	29.08	27.45
9/12/79	23.44	25.79	21.90	25.62	26.78	24.09	24.60
9/18/79	21.27	23.10	19.55	22.03	22.54	20.47	21.49
9/26/79	25.50	26.09	23.57	26.47	27.14	27.03	25.97
9/27/79	24.89	26.21	22.84	25.74	27.19	21.81	24.78
10/23/79	24.65	25.66	23.13	25.91	26.00	25.81	25.19
10/31/79	23.93	24.66	23.70	24.18	24.49	24.81	24.29

Table A7.
Soil moisture content (%) measured by gravimetric method for bare field, plot 8.

Plot 21	Date = 9/26/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	11.29	15.18		
2	10.81	14.26		
3	8.74	14.60		
4	7.60	13.60		
5	15.20	15.73		
6	18.27	22.29		
7	22.50	25.20		
8	19.57	25.01		
9	22.68	23.19		
Ave.	15.18	18.78		

Plot 21	Date = 10/2/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	26.43	31.25	27.08	34.33
2	25.71	25.85	27.94	34.43
3	22.63	24.44	29.91	36.89
4	27.26	28.90	26.84	35.32
5	25.42	25.17	22.98	31.91
6	21.26	23.50	25.21	32.52
7	21.96	23.01	24.28	29.61
8	21.14	23.19	25.14	32.18
9	22.86	23.64	–	31.34
Ave.	23.85	25.44	–	33.17

Plot 21	Date 10/4/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-50.8	5.08–10.16
1	• 17.23	19.71	22.34	27.89
2	17.83	20.90	23.24	30.47
3	21.26	22.62	23.75	27.24
4	17.75	19.69	22.28	27.24
5	17.91	19.15	21.74	28.29
Ave.	18.40	20.41	22.67	28.63

Table A7. (Continued)

Plot (22)	Date = 10/23/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	9.80	15.05	17.43	23.91
2	9.38	15.89	16.92	–
Ave.	9.59	15.47	17.18	23.91

Plot (22)	Date = 10/31/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	8.35	16.92	16.92	19.26
2	13.93	15.12	17.58	23.91
Ave.	11.14	16.02	17.25	21.58

Table A8.
Soil moisture content (%) measured by gravimetric method for bare field, plot 10.

Plot (24)	Date = 10/4/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	31.85	33.20	34.37	39.52
2	30.80	31.14	31.27	36.96
3	30.83	31.02	32.33	38.89
4	30.73	31.30	32.15	37.72
Ave.	31.05	31.66	32.53	38.27

Plot (24)	Date = 10/12/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	28.59	29.84	31.65	38.65
2	31.05	31.10	31.51	39.36
3	30.42	32.02	34.03	39.55
4	29.84	31.27	32.35	37.10
Ave.	29.98	31.06	32.38	38.66

Plot (24)	Date = 10/16/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	28.04	25.44	26.63	33.47
2	26.79	26.97	27.04	30.50
3	27.92	28.38	28.54	34.29
4	28.17	27.77	28.77	34.63
Ave.	27.73	27.14	27.74	33.22

Plot (24)	Date = 10/31/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	23.75	22.84	23.82	14.36
2	24.07	22.88	23.46	33.37
Ave.	23.91	22.86	23.64	23.80

Table A9.
Soil moisture content (%) measured by gravimetric method for corn field, plot 5.

Plot 31	Date 9/26/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54.5.08	5.08-10.16
1	11.02	13.12		
2	14.53	12.88		
3	11.24	12.77		
4	11.48	13.78		
5	19.94	20,87		
6	18.85	18.69		
7	15.96	19.42		
8	11.86	12.44		
9	16.23	15.64		
Ave.	14.57	15.51		

Plot 31	Date = 10/2/79			
Site	Depth (cm)			
	0.1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	24.69	23.23	24.20	25.10
2	24.38	23.14	20.96	23.52
3	24.92	23.58	25.17	26.92
4	22.47	22.66	23.53	24.31
5	27.78	27.93	28.63	31.04
6	28.57	27.92	29.04	29.58
7	26.89	25.57	26.66	29.31
8	24.70	23.83	24.43	25.19
9	27.14	27.42	29.23	28.04
Ave.	25.73	25.03	25.76	27.00

Plot (32)	Date = 10/22/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	15.60	17.46	19.53	21.97
2	18.37	19.44	21.12	22.74
3	19.05	18.92	21.25	21.62
4	13.96	16.54	18.48	19.98
Ave.	16.74	18.09	20.10	21.58

Table A9. (Continued)

Plot (32)	Date = 10/23/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	19.09	18.93	20.22	21.38
2	18.29	18.56	20.53	21.61
3	14.07	16.96	18.34	20.25
Ave.	17.15	18.15	19.70	21.08

Plot (32)	Date = 10/31/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	17.88	18.50	18.73	20.64
2	18.96	19.65	21.54	21.25
3	19.88	19.12	19.67	20.54
4	16.58	17.78	18.82	20.09
Ave.	18.32	18.76	19.69	20.63

Table A10.
Soil moisture content (%) measured by gravimetric method for soybean field, plot 6.

Plot 61 Date = 9/26/79

Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	25.69	25.98		
2	24.28	24.41		
3	24.52	24.83		
4	24.97	24.06		
5	22.45	21.58		
6	22.91	21.77		
7	20.62	19.81		
8	20.39	20.81		
9	24.43	23.96		
Ave.	23.36	23.02		

Plot 61 Date = 10/2/79

Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	33.02	32.36	31.58	31.82
2	30.77	29.97	30.14	31.18
3	30.14	30.95	31.89	31.56
4	29.42	29.85	30.06	30.57
5	29.95	29.75	30.72	31.52
6	29.06	29.23	32.85	30.60
7	29.23	28.72	28.96	30.93
8	28.23	28.62	29.45	28.81
9	30.66	29.98	29.09	29.13
Ave.	30.05	39.94	30.53	30.68

Plot (62) Date = 10/22/79

Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	27.34	26.15	–	–
2	23.33	24.63	23.32	25.38
3	24.96	24.55	–	25.91
4	25.22	25.30	26.27	25.61
Ave.	25.21	25.16	24.80	25.63

Table A10. (Continued)

Plot (62)	Date = 10/23/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	23.22	23.73	24.33	24.25
2	23.43	23.72	24.15	25.92
Ave.	23.32	23.72	24.24	25.08

Plot (62)	Date = 10/31/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	25.28	24.57	–	24.54
2	22.33	23.28	23.29	23.58
3	22.09	22.59	23.65	24.67
4	22.95	22.97	23.73	24.72
Ave.	23.16	23.35	23.56	24.38

Table A11.
Soil moisture content (%) measured by gravimetric method for 10-cm grassland.

Plot (40)	Date = 10/2/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	–	36.56	36.14	35.41
2	–	41.77	38.96	39.37
Ave.	–	39.16	37.55	37.39

Plot (42)	Date = 10/4/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	–	38.43	36.63	35.44
2	36.65	32.41	32.46	31.45
3	39.99	33.60	31.99	33.11
4	44.04	36.96	36.42	36.11
Ave.	40.23	35.35	34.38	34.03

Plot (44)	Date = 10/16/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	47.12	34.57	30.28	33.01
2	39.43	31.40	29.36	28.94
3	49.34	36.12	34.67	35.40
4	41.25	34.61	33.55	33.35
Ave.	44.28	34.18	31.96	32.68

Plot (44)	Date = 10/22/79			
Site		Depth (cm)		
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	37.37	32.56	29.36	29.11

Table A12.
Soil moisture content (%) measured by gravimetric method for 30-cm grassland.

Plot (46)	Date = 10/16/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	–	45.46	41.08	37.29
2	47.56	40.54	40.38	40.59
3	48.83	42.51	42.49	40.47
4	47.66	39.76	38.05	38.68
Ave.	48.02	42.07	40.50	39.26

Plot (46)	Date = 10/22/79			
Site	Depth (cm)			
	0-1.27	1.27-2.54	2.54-5.08	5.08-10.16
1	41.61	33.80	32.32	31.90

Table A13.
Weather Data
USDA NASA Cooperative Soil Moisture-Microwave Experiments Climatic Observations

Date	R	E	T_{AMAX}	T_{AMIN}	T_{WMAX}	T_{WMIN}	W
10/1/79	4.699	1.092	21.1	15.6	28.3	17.8	27.680
10/2/79	0.635	-0.076	22.2	15.6	24.4	18.3	54.240
10/3/79	2.159	0.305	23.9	13.9	24.4	17.8	49.280
10/4/79	0.000	-0.381	22.8	10.0	26.1	15.0	54.400
10/5/79	0.000	-0.279	23.9	14.4	26.1	15.6	80.000
10/6/79	0.000	0.000	20.6	18.3	–	–	80.000
10/7/79	0.000	0.000	27.2	18.9	–	–	80.000
10/8/79	1.295	0.711	21.2	15.6	20.6	7.2	87.680
10/9/79	0.000	-0.914	19.4	11.1	20.6	8.9	87.200
10/10/79	4.115	1.397	20.0	0.6	18.3	5.6	44.640
10/11/79	0.965	0.000	6.7	0.6	7.2	4.4	68.640
10/12/79	0.127	0.178	13.3	6.1	16.7	5.0	34.720
10/13/79	0.000	0.000	17.2	4.4	–	–	34.720
10/14/79	0.025	0.025	16.7	9.4	–	–	34.720
10/15/79	0.000	-0.127	16.7	2.8	15.0	4.4	50.560
10/16/79	0.000	0.229	16.7	2.8	17.8	5.6	6.400
10/17/79	0.000	0.102	18.9	6.1	16.7	9.4	16.000
10/18/79	0.000	0.127	22.8	7.8	21.1	11.1	14.720
10/19/79	0.000	0.229	24.4	7.2	25.0	13.3	46.560
10/20/79	0.000	0.000	-3.9	-17.0	–	–	46.560
10/21/79	0.000	0.000	25.0	12.8	–	–	46.560
10/22/79	0.000	0.787	27.8	11.7	28.9	13.3	62.720
10/23/79	1.407	1.737	28.3	15.6	27.8	17.2	112.32
10/24/79	0.000	-0.991	25.0	4.4	24.4	8.9	93.760
10/25/79	0.000	1.981	11.1	4.4	11.7	4.4	61.760
10/26/79	0.000	0.152	13.3	-0.6	12.8	4.4	37.920
10/27/79	0.000	0.000	8.3	-3.9	–	–	37.920
10/28/79	0.000	0.000	10.0	0.6	–	–	37.920
10/29/79	0.000	0.076	11.1	1.1	13.9	4.4	43.680
10/30/79	0.000	0.203	20.6	0.6	18.3	6.7	30.240
10/31/79	0.000	0.178	17.2	0.6	17.8	6.1	42.120

R = Rainfall (cm)
E = Daily Pan Evaporation (cm)
T_{AMAX} = Maximum Air Temperature (°C)
T_{AMIN} = Minimum Air Temperature (°C)
T_{WMAX} = Maximum Water Temperature (°C)
T_{WMIN} = Minimum Water Temperature (°C)
W = Total Daily Wind Run (Km)

Appendix B

Biomass Data

Table B1.
Relative Biomass and Plant Water per Square Meter for Corn, Soybean and Orchard grass Above Ground Canopies.

Date	Corn		Soybeans		Orchardgrass 30 cm		Orchardgrass 10 cm	
	Biomass	Water	Biomass	Water	Biomass	Water	Biomass	Water
				g/m²				
10/2/79	3057	1845	7435	5768	1959	1589	734	575
10/4/79	3668	2012	–	–	–	–	–	–
10/12/79	2731	1492	4573	3378	990	702	440	332
10/17/79	2537	1389	4072	3009	–	–	–	–
10/22/79	2842	1376	2567	1711				
10/23/79	2675	1350	–	–	869	591	376	278
10/30/79	2382	1238	2183	1033	–	–	–	–

The volume ratio of the dry corn to the air was measured to be about 0.3%.

Appendix C

Soil Moisture and Temperature Data

Date: 10/2/79 Time: 1139-1211

Plot No: 4 Field: Bare

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	216.10	0.52	211.60	0.44
C	10	209.14	0.52	202.08	0.39
C	20	206.12	0.47	191.72	0.33
C	30	211.70	0.48	187.28	0.38
C	40	221.23	0.53	178.54	0.37
C	50	234.67	0.59	174.22	0.31
C	60	247.31	0.48	162.74	0.39
C	70	260.69	0.48	136.56	0.37
L	0	209.17	1.08	214.20	1.16
L	10	204.81	1.06	207.08	1.40
L	20	205.11	1.16	200.20	1.35
L	30	208.60	1.28	198.70	1.63
L	40	214.19	1.06	182.95	1.18
L	50	226.86	1.06	173.07	1.21
L	60	237.33	1.07	153.45	1.34
L	70	247.81	1.15	125.38	1.28

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	16.99	17.39	17.37

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
23.3	21.9	20.5

Date: 10/4/79 | Time: 0908-0947

Plot No: 5 | Field: Bare

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	204.17	0.94	203.19	0.47
C	10	187.40	0.66	181.05	0.28
C	20	189.22	0.72	174.56	0.32
C	30	194.62	0.65	166.85	0.31
C	40	206.00	0.60	158.03	0.30
C	50	221.55	0.67	144.23	0.35
C	60	240.52	0.69	125.14	0.35
C	70	258.52	0.71	91.15	0.36
L	0	207.29	0.99	206.97	3.08
L	10	186.15	0.98	184.02	1.29
L	20	190.58	1.23	180.23	1.29
L	30	196.18	2.28	173.09	1.50
L	40	205.28	1.11	165.22	1.42
L	50	218.03	1.38	152.52	1.27
L	60	230.04	1.26	133.47	1.14
L	70	238.68	1.23	105.44	1.34

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	23.76	25.05	26.85

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
21.00	18.20	17.20

Date: 10/12/79 Time: 0928-1022

Plot No.: 5 Field: Bare

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	191.42	0.62	191.88	0.25
C	10	184.19	0.68	176.65	0.27
C	20	186.57	4.19	172.51	3.87
C	30	187.69	0.61	160.46	0.29
C	40	198.41	0.66	153.38	0.28
C	50	215.43	0.64	141.44	0.26
C	60	234.86	0.70	121.06	0.45
C	70				
L	0	189.52	0.98	190.39	1.43
L	10	180.24	0.93	177.25	1.67
L	20	179.83	1.00	169.58	1.11
L	30	185.62	1.09	163.21	1.37
L	40	194.16	1.09	155.37	1.26
L	50	206.81	1.04	143.33	1.60
L	60	219.89	0.92	120.96	1.25
L	70				

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	22.00	24.76	25.10

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
14.70	12.78	11.00

Date: 10/12/79 Time: 1124-1248

Plot No.: 4 Field: Bare

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	196.13	0.57	194.60	0.27
C	10	191.62	0.54	185.17	0.32
C	20	192.22	0.61	178.70	0.32
C	30	196.71	0.65	170.27	0.35
C	40	208.61	0.66	161.64	0.37
C	50	227.61	0.59	158.58	0.34
C	60	242.16	0.60	130.66	0.48
C	70	254.37	0.57	120.35	0.52
L	0	211.76	0.95	208.99	1.15
L	10	204.62	2.32	201.75	1.43
L	20	205.71	0.97	197.11	1.22
L	30	207.69	1.05	186.22	1.59
L	40	216.71	1.71	179.41	1.30
L	50	227.67	0.96	169.98	1.47
L	60	236.54	1.20	146.67	1.36
L	70	239.59	1.05	120.56	1.48

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	14.85	16.81	17.90

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
25.2	20.50	14.61

Date: 10/15/79 Time: 0935-1016

Plot No.: 4 Field: Bare

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	203.20	0.67	221.05	0.60
C	10	201.58	0.67	194.16	0.35
C	20	204.67	0.66	190.82	0.30
C	30	205.49	0.57	180.37	0.28
C	40	215.98	0.57	173.42	0.23
C	50	234.19	0.59	*174.25	0.33
C	60	245.78	0.68	156.38	0.32
C	70	252.39	0.85	131.85	0.39
L	0	216.03	0.98	216.12	1.59
L	10	202.14	1.07	200.24	1.32
L	20	205.67	1.24	197.73	1.25
L	30	210.45	1.26	189.68	1.48
L	40	222.33	7.31	181.11	1.39
L	50	227.65	1.19	172.90	1.31
L	60	240.43	1.10	*205.77	1.51
L	70	245.43	3.91	137.92	1.53

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	13.06	15.71	16.74

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
14.00	13.00	8.67

*Contamination due to RFI.

Date: 10/16/79

Time: 0819-0909

Plot No.: 5

Field: Bare

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	178.75	2.85	177.29	2.14
C	10	182.89	0.77	175.29	0.23
C	20	185.93	0.72	169.44	0.29
C	30	190.17	0.68	159.64	0.31
C	40	200.89	0.68	151.80	0.36
C	50	216.46	0.78	145.73	0.28
C	60	229.93	0.65	141.86	1.20
C	70	245.44	0.68	115.02	0.36
L	0	200.41	1.08	190.55	1.19
L	10	194.77	1.24	183.84	1.51
L	20	198.16	1.24	179.75	1.30
L	30	198.70	4.15	170.94	1.48
L	40	208.95	1.40	164.37	1.12
L	50	217.70	1.01	157.77	1.52
L	60	225.62	0.99	139.13	1.23
L	70	233.15	1.09	113.95	1.55

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	21.10	22.07	23.16

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
12.00	10.83	10.67

Date: 10/16/79 Time: 0931-1014

Plot No.: 4 Field: Bare

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	216.89	0.60	215.97	0.39
C	10	206.72	0.65	202.63	0.30
C	20	205.91	0.75	195.34	0.39
C	30	212.84	0.72	188.94	0.28
C	40	226.02	0.62	184.07	0.28
C	50	237.77	0.63	172.18	0.31
C	60	251.05	0.55	148.28	0.29
C	70	261.03	0.64	126.25	0.32
L	0	217.02	1.39	217.68	1.59
L	10	207.84	1.10	206.74	1.67
L	20	210.65	1.42	202.21	1.22
L	30	215.84	1.16	196.61	1.16
L	40	221.47	1.21	187.87	1.51
L	50	231.19	1.27	178.12	1.26
L	60	240.20	1.10	203.66*	1.37
L	70	241.80	1.27	131.79	1.26

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	15.09	16.07	16.85

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
13.20	12.17	10.61

Date: 10/16/79 Time: 1048-1125

Plot No.: 3 Field: Bare

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	227.42	0.57	249.07	0.32
C	10	218.55	0.53	214.60	0.28
C	20	217.27	0.54	208.49	0.29
C	30	222.28	0.58	201.34	0.28
C	40	231.00	0.57	192.43	0.36
C	50	241.72	0.62	180.38	0.34
C	60	254.27	0.62	161.63	0.30
C	70	260.46	0.65	139.25	0.28
L	0	233.88	1.24	234.87	1.54
L	10	229.80	1.26	227.28	1.58
L	20	230.24	1.24	220.65	1.56
L	30	231.09	1.24	212.14	1.55
L	40	236.25	1.32	202.10	1.24
L	50	242.92	1.30	187.52	1.22
L	60	248.19	1.13	170.76	1.19
L	70	250.49	1.76	139.75	1.20

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	10.99	13.58	14.68

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
16.00	13.28	11.39

Date: 10/22/79 Time: 1102-1201

Plot No.: 4 Field: Bare

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	245.72	0.56	231.02	0.79
C	10	241.66	0.55	238.13	0.28
C	20	240.39	0.49	227.13	0.35
C	30	247.14	0.47	226.03	0.27
C	40	258.80	0.48	221.29	0.30
C	50	268.98	0.54	208.25	0.33
C	60	275.75	0.56	181.51	0.48
C	70	270.44	0.59	151.84	0.50
L	0	250.04	1.34	248.79	1.56
L	10	250.21	1.48	243.70	2.13
L	20	246.95	1.17	236.84	1.55
L	30	252.25	1.15	229.26	1.52
L	40	256.74	1.21	221.62	1.63
L	50	260.63	1.05	206.26	1.62
L	60	265.46	1.14	183.81	1.50
L	70	256.12	1.09	151.90	1.27

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	9.81	12.14	14.19

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
29.00	22.11	19.33

Date: 10/23/79 Time: 1359-1435

Plot No.: 4 Field: Bare

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	261.94	0.47	262.11	0.32
C	10	261.83	0.52	259.74	0.28
C	20	260.66	0.51	253.80 0.851	0.31
C	30	263.62	0.46	248.42	0.28
C	40	268.95	0.54	240.88	0.27
C	50	273.99	0.56	228.62	0.32
C	60	275.72	0.55	202.45	0.32
C	70	265.38	0.60	175.77	0.33
L	0	256.54	1.27	255.97	1.68
L	10	256.37	1.20	250.78	1.60
L	20	257.90	1.26	245.56 0.831	1.39
L	30	260.63	1.18	238.14	1.66
L	40	267.46	2.10	229.10	1.55
L	50	270.45	1.14	218.39	1.85
L	60	268.71	1.26	196.00	1.26
L	70	254.21	1.22	159.43	1.49

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
4.98	10.04	12.87	15.50

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
25.10	22.33	21.39

Date: 10/24/79 Time: 1302-1357

Plot No.: 4 Field: Bare

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	194.97	0.49	196.51	0.27
C	10	193.79	0.56	190.40	0.26
C	20	192.92	0.58	183.53	0.31
C	30	197.51	0.69	176.99	0.34
C	40	208.00	0.56	166.93	0.27
C	50	220.99	0.56	154.28	0.35
C	60	237.66	0.59	135.24	0.30
C	70	251.85	0.76	109.03	0.55
L	0	220.09	2.08	215.19	2.34
L	10	206.26	0.97	203.96	1.46
L	20	206.13	0.98	196.75	1.42
L	30	213.51	1.09	188.64	1.47
L	40	219.07	1.27	175.97	1.24
L	50	229.11	1.32	164.54	1.33
L	60	241.47	1.27	144.95	1.19
L	70	250.21	1.59	118.49	1.25

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	16.92	18.58	18.91

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
10.45	11.33	12.11

Date: 10/25/79 Time: 1355-1434

Plot No.: 4 Field: Bare

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	202.30	0.61	199.61	0.93
C	10	202.34	0.56	197.60	0.32
C	20	203.00	0.60	192.14	0.30
C	30	210.44	0.56	184.50	0.28
C	40	220.68	0.60	176.80	0.35
C	50	233.47	0.60	164.88	0.39
C	60	247.97	0.53	141.02	0.44
C	70	256.95	0.63	115.76	1.23
L	0	227.56	1.43	219.26	1.45
L	10	222.85	1.21	210.96	1.10
L	20	224.69	1.32	205.83	1.27
L	30	228.27	1.44	196.67	1.30
L	40	229.45	1.15	188.01	1.47
L	50	233.26	1.13	181.94	1.53
L	60	251.77	0.95	156.00	1.28
L	70	251.41	1.06	121.56	1.14

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
	12.23	15.68	16.83

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
12.50	11.89	11.11

Date: 10/29/79 Time: 1336-1421

Plot No.: 4 Field: Bare

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	251.07	0.48	250.90	0.78
C	10	244.45	0.51	241.53	0.31
C	20	242.88	0.55	235.56 0.800	0.29
C	30	246.26	0.51	230.27	0.30
C	40	252.68	0.54	220.88	0.26
C	50	258.63	0.49	207.22	0.36
C	60	267.87	0.59	185.37	0.40
C	70	263.84	0.61	154.94	0.42
L	0	243.53	1.23	243.07	1.45
L	10	239.57	1.26	237.33	1.65
L	20	238.30	1.18	231.33 0.787	1.51
L	30	239.04	1.04	223.51	1.49
L	40	241.19	1.29	209.26	1.45
L	50	243.18	1.12	190.05	1.22
L	60	252.91	1.15	177.50	1.38
L	70	244.07	1.22	145.20	1.44

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
6.37	10.94	12.81	13.84

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
21.25	17.22	15.28

Date: 10/29/79 Time: 1425-1503

Plot No.: 5 Field: Bare

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	209.43	2.00	206.15	0.35
C	10	199.00	0.58	193.22	0.35
C	20	199.95	0.55	186.78 0.635	0.28
C	30	204.56	0.57	177.85	0.34
C	40	215.61	0.61	168.10	0.34
C	50	230.22	0.60	153.84	0.38
C	60	246.06	0.59	135.67	0.46
C	70	260.43	0.64	133.03	0.55
L	0	210.82	1.20	208.13	1.24
L	10	201.03	1.01	195.28	1.43
L	20	202.80	0.99	188.45 0.647	1.26
L	30	210.05	0.94	181.07	1.47
L	40	217.55	1.16	172.48	1.80
L	50	229.57	1.10	157.62	1.37
L	60	242.80	0.98	139.47	1.28
L	70			125.54	1.37

Soil Moisture Data (%)

0-0.50 cm	0–2.5 cm	2.5-5 cm	5-10 cm
18.36	19.61	19.61	20.33

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
21.00	18.17	12.97

Date: 10/2/79 Time: 0945-1013

Plot No.: 1 Field: Corn (1)

Freq.	Angle	Angle A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	253.64	0.52	250.10	0.28
C	10	255.34	0.44	251.73	0.28
C	20	259.03	0.46	250.86	0.30
C	30	261.05	0.45	248.68	0.31
C	40	266.44	0.53	251.12	0.28
C	50	271.94	0.45	252.99	0.27
C	60	275.18	0.36	256.37	0.31
C	70	275.27	0.52	258.43	0.30
L	0	257.06	1.44	257.65	1.63
L	10	254.64	1.02	251.59	1.27
L	20	257.42	1.16	245.03	1.62
L	30	260.07	1.63	240.20	1.54
L	40	260.44	1.16	235.53	1.75
L	50	260.37	1.19	231.58	1.37
L	60	256.83	1.24	224.41	1.34
L	70	249.24	1.21	220.76	1.26

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	16.00	16.00	15.90

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
19.5	19.7	19.6

Date: 10/2/79 | Time: 1335-1425

Plot No.: | Field: Grass (30 cm)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	281.13	0.48	261.19	0.37
C	10	279.69	0.56	276.75	0.42
C	20	275.66	0.58	272.39	0.30
C	30	276.82	0.58	271.60	0.29
C	40	278.92	0.58	271.85	0.31
C	50	280.39	0.54	271.89	0.35
C	60	282.31	0.60	270.39	0.38
C	70	283.15	0.46	271.58	0.29
L	0	235.33	1.33	234.39	1.37
L	10	236.02	1.38	228.03	1.15
L	20	237.01	1.21	223.97	1.39
L	30	234.62	1.21	221.29	1.36
L	40	247.65	8.91	224.47	8.92
L	50	241.05	0.97	213.87	1.37
L	60	242.74	1.32	205.68	1.56
L	70	224.08	1.04	194.40	1.43

Soil Moisture Data (%)

0-0.50 cm	0.25 cm	2.5-5 cm	5-10 cm
–	24.03	21.55	20.68

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
28.0	25.4	21.6

Date: 10/2/79 Time: 1024-1058

Plot No.: 2 Field: Soybean (1)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	273.16	0.48	269.48	0.30
C	10	273.56	0.44	269.61	0.32
C	20	273.13	0.50	270.24	0.31
C	30	273.30	0.46	271.28	0.33
C	40	273.47	0.52	270.36	0.31
C	50	272.57	0.46	269.30	0.28
C	60	271.44	0.51	267.19	0.33
C	70	266.40	0.46	263.72	0.27
L	0	258.83	1.21	259.03	1.51
L	10	259.92	1.50	256.64	1.77
L	20	261.20	1.03	255.79	1.35
L	30	258.55	1.19	254.68	1.54
L	40	258.13	3.43	252.63	2.12
L	50	257.90	1.25	250.30	1.60
L	60	258.33	1.16	256.64	1.31
L	70	248.24	1.28	248.97	1.30

Soil Moisture Data (%)

0.0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	19.61	20.49	20.74

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
22.0	21.2	20.1

Date: 10/4/79 Time: 1059-1130

Plot No.: Field: Grass (10 cm)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	265.64	0.37	264.09	0.26
C	10	263.44	0.57	260.72	0.34
C	20	260.91	0.51	257.26	0.30
C	30	262.42	0.54	255.93	0.32
C	40	265.46	0.64	254.93	0.34
C	50	269.70	0.52	255.05	0.29
C	60	272.66	0.61	255.02	0.34
C	70	275.68	0.47	258.24	0.35
L	0	222.99	1.03	223.89	1.34
L	10	223.98	1.17	217.48	1.55
L	20	222.27	1.15	212.14	1.25
L	30	221.82	0.97	207.10	1.79
L	40	224.01	0.92	200.53	1.43
L	50	227.67	1.16	195.13	1.48
L	60	231.62	1.20	184.88	1.48
L	70	221.37	1.08	166.83	1.33

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	19.30	18.63	19.42

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
25.50	24.44	20.50

Date: 10/15/79 Time: 1056-1130

Plot No.: 2 Field: Soybean (1)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	270.04	0.47	269.36	0.43
C	10	268.86	0.47	267.03	0.29
C	20	265.28	0.47	264.48	0.32
C	30	264.57	0.49	263.68	0.28
C	40	265.38	0.53	264.68	0.34
C	50	264.94	0.47	264.17	0.27
C	60	263.42	0.62	262.66	0.31
C	70	259.84	0.48	260.04	0.26
L	0	253.29	7.21	246.07	2.07
L	10	241.72	1.22	239.61	1.57
L	20	242.30	1.32	236.21	1.27
L	30	244.10	1.27	234.50	1.46
L	40	247.74	1.28	237.79	1.11
L	50	251.43	1.13	238.70	1.47
L	60	250.42	1.13	238.27	1.32
L	70	241.55	1.07	236.96	1.66

Soil Moisture Data (%)

0-0.50 cm	0–2.5 cm	2.5-5 cm	5-10 cm
–	18.00	19.90	18.80

Soil Temperature Data (°C)

Ambient	0-2.5 cm	10-12.5 cm
14.75	9.69	9.06

Date: 10/15/79 Time: 1422-1506

Plot No.: 1 Field: Corn (1)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	231.21	0.68		
C	10	221.76	0.58	217.31	0.26
C	20	225.18	0.63	214.57	0.26
C	30	229.95	0.66	211.46	0.29
C	40	239.38	0.46	211.33	0.29
C	50	250.87	0.59	213.47	0.33
C	60	259.96	0.59	212.99	0.40
C	70	265.77	0.49	219.25	0.79
L	0	251.77	1.22	250.40	1.36
L	10	248.87	1.18	244.30	1.83
L	20	253.51	1.19	240.14	1.40
L	30	257.10	1.11	231.99	1.47
L	40	257.81	1.10	225.85	0.98
L	50	256.88	1.34	218.09	1.76
L	60	255.79	1.18	207.78	1.47
L	70	248.41	1.13	196.45	1.62

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	16.76	18.30	16.50

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
18.50	17.12	13.30

Date: 10/15/79 Time: 1312-1354

Plot No.: 1 Field: Corn (11)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	223.88	0.52	224.06	0.38
C	10	220.57	0.51	219.07	0.34
C	20	221.08	0.61	214.80	0.30
C	30	223.54	0.60	208.95	0.27
C	40	235.15	0.59	206.13	0.28
C	50	245.87	0.52	199.57	0.31
C	60	257.68	0.63	194.84	0.27
C	70	264.89	0.54	192.83	0.41
L	0	243.76	1.12	246.38	1.58
L	10	239.23	1.16	237.39	1.78
L	20	242.45	1.10	233.25	1.58
L	30	244.07	1.19	226.47	1.36
L	40	247.40	0.89	221.57	1.46
L	50	249.96	1.01	213.54	1.33
L	60	253.04	1.19	206.90	1.33
L	70	247.80	1.10	200.74	1.44

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	14.39	15.83	15.56

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
18.00	14.73	11.89

Date: 10/16/79 Time: 1317-1336

Plot No.: Field: Grass (30 cm)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	265.01	0.52	244.38	0.42
C	10	265.29	0.48	264.52	0.33
C	20	260.40	0.52	260.14	0.32
C	30	267.70	0.56	263.44	0.39
C	40	270.75	0.48	260.11	0.35
C	50	275.60	0.46	264.51	0.34
C	60	277.79	0.54	267.95	0.34
C	70	277.59	0.54	268.63	0.36
L	0	231.71	1.16	230.96	1.60
L	10	225.32	1.03	228.48	1.69
L	20	225.80	1.05	220.26	1.28
L	30	228.74	1.24	214.06	1.52
L	40	234.96	1.11	208.54	1.48
L	50	243.83	1.18	231.42*	1.34
L	60	250.09	1.15	208.66*	1.43
L	70	245.83	0.98	187.88	1.23

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	25.15	24.75	23.18

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
21.30	14.19	12.22

Date: 10/16/79 Time: 1341-1419

Plot No.: Field: Grass (30 cm)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	268.68	0.54	266.54	0.28
C	10	267.35	0.48	264.89	0.29
C	20	263.86	0.46	261.66	0.30
C	30	265.95	0.49	261.52	0.32
C	40	268.54	0.47	261.41	0.32
C	50	272.54	0.49	263.20	0.36
C	60	272.16	0.49	263.23	0.30
C	70	274.25	0.43	265.57	0.28
L	0	229.41	1.10	228.06	1.62
L	10	221.79	1.26	221.26	1.70
L	20	222.77	1.10	215.92	1.29
L	30	226.24	1.05	210.28	1.47
L	40	230.92	1.14	206.58	1.40
L	50	235.85	1.18	198.96	1.42
L	60	242.28	0.99	195.02*	1.26
L	70	242.43	1.25	177.41	1.42

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	23.91	23.47	22.62

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
21.20	14.39	12.22

Date: 10/16/79 Time: 1436-1511

Plot No.: Field: Grass (10 cm)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	261.78	0.51	261.79	0.34
C	10	257.82	0.57	256.44	0.35
C	20	254.84	0.50	252.55	0.36
C	30	255.63	0.43	250.27	0.38
C	40	258.42	0.52	249.04	0.34
C	50	262.83	0.81	248.18	0.29
C	60	267.01	0.55	250.00	0.38
C	70	268.55	0.48	255.38	0.72
L	0	217.97	1.01	217.92	1.98
L	10	211.46	1.12	208.07	1.55
L	20	213.57	1.09	207.56	1.47
L	30	215.57	1.19	200.03	1.67
L	40	222.47	1.10	202.58	1.22
L	50	224.96	1.38	190.51	1.51
L	60	233.51	1.23	171.45	1.14
L	70	227.72	2.52	145.69	1.33

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	19.44	18.65	17.86

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
21.50	16.56	14.11

Date: 10/22/79 Time: 1359-1434

Plot No.: 2 Field: Soybean (11)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	270.04	0.50	251.70	0.72
C	10	269.48	0.44	269.13	0.35
C	20	266.85	0.49	267.31	0.32
C	30	268.11	0.51	265.80	0.31
C	40	269.55	0.47	264.80	0.37
C	50	269.87	0.45	263.79	0.28
C	60	267.92	0.55	263.56	0.43
C	70	264.43	0.65	260.68	0.41
L	0	258.50	1.25	251.79	1.32
L	10	252.91	1.08	245.03	1.65
L	20	255.90	1.20	240.95	1.39
L	30	252.45	1.40	237.21	1.32
L	40	255.75	1.46	233.89	1.65
L	50	259.37	1.12	228.91	1.56
L	60	263.03	0.98	228.94	1.51
L	70	257.70	1.30	232.15	1.62

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	17.61	17.77	17.55

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
30.70	25.28	20.17

Date: 10/22/79 Time: 1456-

Plot No.: 1 Field: Corn (1)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	253.87	0.45	238.29	0.34
C	10	253.64	0.54	248.62	0.25
C	20	253.31	0.56	242.89	0.36
C	30	256.02	0.53	238.21	0.25
C	40	263.49	0.50	237.26	0.29
C	50	271.14	0.60	234.40	0.32
C	60	279.74	0.56	233.20	0.52
C	70	278.91	0.50	239.88	1.39
L	0	270.30	1.31	267.64	1.58
L	10	268.18	1.39	260.78	1.66
L	20	271.68	1.30	255.98	1.58
L	30	273.68	1.35	249.50	1.62
L	40	274.26	1.58	240.08	1.45
L	50	269.45	1.25	230.57	1.24
L	60	271.72	1.46	219.65	1.47
L	70	260.65	1.10	205.37	1.41

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	10.75	11.25	13.03

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
29.75	27.94	23.61

Date: 10/23/79 Time: 0800-0840

Plot No.: 1 Field: Corn (1)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	250.57	0.46	274.82	1.02
C	10	249.40	0.43	247.07	0.25
C	20	250.66	0.47	244.18	0.31
C	30	254.70	0.44	241.95	0.28
C	40	260.71	0.48	241.86	0.30
C	50	266.84	0.51	239.67	0.25
C	60	271.52	0.45	240.88	0.25
C	70	273.59	0.51	247.29	0.80
L	0	270.30	1.98	259.37	1.30
L	10	262.16	1.42	253.48	1.72
L	20	270.97	1.12	249.33	1.51
L	30	264.09	1.24	242.85	1.51
L	40	263.09	1.12	236.02	1.80
L	50	261.31	1.34	225.98	1.78
L	60	261.46	1.24	216.25	1.32
L	70	254.12	1.24	205.46	1.51

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	10.75	11.43	12.00

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
18.50	17.78	16.67

Date: 10/23/79 Time: 0841-0927

Plot No.: 1 Field: Corn (1)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	248.40	0.46	248.24	0.32
C	10	247.94	0.45	244.12	0.30
C	20	247.92	0.51	239.72	0.31
C	30	251.27	0.41	236.98	0.26
C	40	258.15	0.46	237.54	0.30
C	50	264.78	0.56	235.81	0.31
C	60	270.12	0.48	237.53	0.38
C	70	272.69	0.47	244.38	0.32
L	0	265.42	1.79	260.81	1.60
L	10	263.52	1.39	254.03	1.29
L	20	261.84	1.21	248.13	1.36
L	30	266.42	3.78	242.39	1.60
L	40	269.11	2.44	235.37	1.60
L	50	260.87	1.30	224.31	1.32
L	60	262.58	1.79	215.51	1.52
L	70	254.08	1.19	204.92	1.19

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	10.33	10.90	12.05

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
20.00	18.56	17.22

Date: 10/23/79 Time: 0940-1037

Plot No.: 2 Field: Soybean (1)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	246.82	0.49	244.92	0.30
C	10	246.28	0.59	246.97	0.27
C	20	255.02	0.53	255.43	0.30
C	30	260.36	0.45	259.78	0.35
C	40	262.84	0.45	260.98	0.26
C	50	263.06	0.49	259.41	0.29
C	60	263.41	0.48	260.37	0.27
C	70	259.17	0.56	256.12	0.77
L	0	243.16	1.19	237.55	1.43
L	10	235.90	1.01	230.72	1.50
L	20	239.93	1.11	230.09	1.32
L	30	244.21	1.20	227.52	1.44
L	40	248.68	1.09	224.48	1.38
L	50	252.12	1.45	219.83	1.52
L	60	255.24	1.22	220.74	1.32
L	70	245.31	1.17	214.52	1.23

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	17.20	20.04	17.24

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
22.00	18.44	15.61

Date: 10/23/79 Time: 1202-1236

Plot No.: Field: Grass (30 cm)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	273.46	0.53	274.09	0.38
C	10	273.54	0.48	275.08	0.29
C	20	272.73	0.56	271.73	0.33
C	30	276.01	0.51	271.80	0.33
C	40	277.66	0.47	268.69	0.23
C	50	281.99	0.49	272.80	0.29
C	60	285.02	0.48	276.75	0.33
C	70	284.96	0.52	276.96	0.37
L	0	249.22	1.20	234.47	1.67
L	10	234.63	1.22	233.06	1.95
L	20	238.52	2.04	227.22	1.43
L	30	237.69	0.95	221.63	1.30
L	40	247.00	1.22	215.87	1.17
L	50	260.27	1.30	249.69*	1.74
L	60	260.38	1.06	219.56*	1.52
L	70	253.82	2.61	201.19	1.76

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	28.05	22.40	21.82

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
25.50	19.17	16.72

Date: 10/23/79 Time: 1249-1324

Plot No.: Field: Grass (10 cm)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	258.34	0.52	260.22	0.29
C	10	256.87	0.48	257.50	0.33
C	20	253.10	0.49	252.69	0.30
C	30	255.06	0.48	251.80	0.33
C	40	259.67	0.50	252.55	0.30
C	50	266.24	0.47	253.75	0.30
C	60	270.93	0.51	254.68	0.31
C	70	272.72	0.51	257.02	0.42
L	0	231.74	1.34	233.39	1.48
L	10	224.61	1.24	218.54	2.04
L	20	223.30	1.60	212.61	1.39
L	30	226.56	1.71	207.04	1.68
L	40	234.58	1.37	204.91*	1.64
L	50	245.27	1.17	234.04*	1.47
L	60	238.86	1.16	176.08	1.53
L	70	233.37	1.23	135.38	1.39

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	21.66	18.17	17.89

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
25.00	20.64	19.17

Date: 10/24/79 Time: 0758-0839

Plot No.: 1 Field: Corn (1)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	232.10	0.54	234.03	0.78
C	10	230.53	0.44	229.41	0.32
C	20	229.38	0.51	223.75	0.27
C	30	232.28	0.51	219.80	0.28
C	40	240.11	0.51	220.01	0.23
C	50	249.27	0.46	220.09	0.26
C	60	257.41	0.50	221.77	0.24
C	70	261.12	0.59	228.74	0.38
L	0	238.01	1.28	237.57	1.65
L	10	239.23	1.14	228.21	1.45
L	20	240.56	1.72	224.12	1.38
L	30	243.38	1.13	218.91	1.34
L	40	246.55	1.27	211.70	1.71
L	50	250.64	1.28	202.68	1.37
L	60	248.84	1.20	194.11	1.53
L	70	244.44	1.13	183.87	1.37

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	15.21	15.85	15.56

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
7.00	9.33	11.11

Date: 10/24/79 Time: 0839-0912

Plot No.: 1 Field: Corn (1)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	231.11	0.50	233.25	0.28
C	10	225.81	0.54	223.43	0.24
C	20	225.80	0.53	219.93	0.33
C	30	229.11	0.51	215.51	0.24
C	40	238.09	0.62	215.80	0.33
C	50	248.52	0.64	223.35	1.84
C	60	256.51	0.50	220.57	0.30
C	70	261.72	0.59	229.34	0.38
L	0	241.68	1.34	235.97	1.49
L	10	234.76	1.17	228.05	1.73
L	20	239.44	2.40	223.16	1.33
L	30	243.71	1.22	218.23	1.51
L	40	244.66	1.12	211.37	1.19
L	50	243.54	1.07	201.86	1.33
L	60	252.36	1.11	194.38	1.49
L	70	244.54	1.13	183.97	1.37

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	14.71	14.88	15.34

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
7.95	9.44	11.06

Date: 10/24/79 Time: 0938-1002

Plot No.: Field: Grass (30 cm)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	272.06	0.39	298.76	0.55
C	10	270.38	0.44	269.57	0.28
C	20	266.53	0.48	266.76	0.29
C	30	267.03	0.56	266.10	0.27
C	40	268.44	0.42	265.98	0.25
C	50	269.81	0.47	267.07	0.32
C	60	270.24	0.52	266.23	0.32
C	70	269.47	0.51	265.41	0.31
L	0	244.80	0.83	238.44	1.30
L	10	236.47	1.00	229.60	1.43
L	20	234.69	2.94	222.35	1.47
L	30	232.51	1.33	219.96	1.33
L	40	244.43	1.18	220.99	1.12
L	50	243.61	1.78	216.28	1.43
L	60	242.43	1.24	206.79	1.52
L	70	240.50	1.19	190.57	1.48

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	27.33	23.34	23.03

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
10.70	12.06	12.72

Date: 10/24/79 Time: 1018-1100

Plot No.: Field: Grass (10 cm)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	263.30	0.50	264.58	0.28
C	10	261.04	0.55	262.03	0.28
C	20	258.32	0.52	258.95	0.31
C	30	259.04	0.47	258.52	0.32
C	40	264.39	0.45	262.71	0.26
C	50	261.51	0.54	256.88	0.37
C	60	263.23	0.50	257.74	0.25
C	70	261.78	0.49	253.68	0.28
L	0	225.94	1.09	221.35	1.43
L	10	214.29	2.35	209.67	1.34
L	20	213.38	1.09	206.34	1.37
L	30	219.39	4.17	198.50	1.46
L	40	219.85	1.12	194.57	1.38
L	50	222.07	1.45	178.91	1.39
L	60	225.42	1.09	160.94	1.38
L	70	218.82	0.92	130.21	1.46

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	17.82	16.73	17.06

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
10.55	12.89	13.39

Date: 10/24/79 Time: 1226-1258

Plot No.: 2 Field: Soybean (11)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	255.52	0.46	280.72	0.62
C	10	254.50	0.44	253.56	0.29
C	20	251.42	0.63	250.95	0.35
C	30	252.00	0.50	250.02	0.35
C	40	252.70	0.48	247.76	0.29
C	50	252.71	0.51	245.92	0.25
C	60	251.36	0.51	244.68	0.26
C	70	245.80	0.62	241.18	0.31
L	0	232.88	1.07	233.17	1.63
L	10	227.45	1.23	226.35	1.53
L	20	229.21	1.21	222.87	1.67
L	30	235.86	1.26	217.25	1.34
L	40	239.27	1.20	211.07	1.66
L	50	236.44	1.12	205.46	1.31
L	60	244.78	1.70	204.21	1.43
L	70	243.09	1.11	205.83	1.40

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	21.28	22.12	19.65

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
10.65	12.44	13.06

Date: 10/25/79 Time: 0814-0847

Plot No.: Field: Grass (30 cm)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	264.90	0.49	266.92	0.54
C	10	267.49	0.45	267.24	0.36
C	20	262.62	0.43	263.41	0.26
C	30	265.34	0.49	261.41	0.24
C	40	269.14	0.51	265.35	0.42
C	50	268.80	0.48	267.65	0.27
C	60	269.86	0.49	262.74	0.43
C	70	268.46	0.49	262.81	0.35
L	0	234.35	3.46	226.28	1.45
L	10	231.70	1.19	223.74	1.45
L	20	233.76	1.25	220.15	1.43
L	30	234.10	3.55	214.06	1.42
L	40	242.48	1.25	210.98	1.54
L	50	247.96	1.19	207.90*	1.73
L	60	245.96	1.03	205.31*	1.63
L	70	242.93	1.28	189.34	1.53

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	24.65	25.15	23.80

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
6.60	9.08	10.39

Date: 10/25/79 Time: 0859-0944

Plot No.: Field: Grass (10 cm)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	256.33	0.45	256.43	0.33
C	10	252.75	0.51	252.68	0.30
C	20	249.33	0.48	249.66	0.28
C	30	250.25	0.48	248.85	0.25
C	40	252.30	0.43	249.06	0.27
C	50	255.35	0.47	249.44	0.24
C	60	256.91	0.48	251.16	0.30
C	70	253.02	0.50	247.27	0.30
L	0	218.17	1.12	213.52	1.74
L	10	204.29	1.05	196.32	1.40
L	20	203.14	1.25	191.92	1.38
L	30	207.07	1.52	186.58	1.27
L	40	211.33	1.22	178.96	1.32
L	50	219.56	1.24	165.84	1.57
L	60	225.87	1.14	144.10	1.42
L	70	216.63	3.44	116.93	1.46

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	21.09	16.47	14.79

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
12.75	9.03	8.42

Date: 10/25/79

Time: 1028-1106

Plot No.:

Field: Corn (1)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	226.62	0.60	215.47	0.88
C	10	228.11	0.55	224.58	0.28
C	20	227.66	0.50	220.48	0.28
C	30	231.97	0.49	215.56	0.28
C	40	239.26	0.52	214.40	0.30
C	50	248.00	0.51	212.10	0.30
C	60	256.42	0.48	210.42	0.33
C	70	260.16	0.55	215.12	0.31
L	0	242.04	1.56	240.16	1.38
L	10	243.42	1.31	231.76	1.55
L	20	247.10	1.34	226.53	1.24
L	30	251.62	1.20	220.78	1.48
L	40	248.90	3.19	214.28	1.69
L	50	253.03	1.75	203.98	1.30
L	60	252.41	1.28	193.88	1.49
L	70	244.06	1.27	180.40	1.51

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	14.23	13.68	14.07

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
10.50	9.28	8.89

Date: 10/29/79 Time: 1001-1052

Plot No.: 1 Field: Corn (11)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	240.49	0.59	242.34	0.30
C	10	236.06	0.51	234.41	0.30
C	20	234.29	0.53	230.09	0.22
C	30	237.90	0.51	228.17	0.25
C	40	243.36	0.62	225.32	0.39
C	50	249.89	0.43	220.19	0.29
C	60	257.07	0.46	221.56	0.29
C	70	257.94	0.51	221.71	0.31
L	0	241.92	1.11	235.38	1.50
L	10	227.78	1.42	225.08	1.38
L	20	236.20	1.17	220.70	1.42
L	30	238.21	1.29	213.42	1.52
L	40	243.47	0.90	204.46	1.38
L	50	242.89	1.12	195.39	1.44
L	60	243.62	1.04	186.94	1.38
L	70	244.02	1.12	180.87	1.35

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	12.70	12.84	13.55

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
16.40	11.39	9.56

Date: 10/25/79 Time: 1247-1330

Plot No.: 2 Field: Soybean (1)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0				
C	10	244.18	0.53	245.86	0.28
C	20	244.73	0.48	246.57	0.31
C	30	246.75	0.47	246.95	0.31
C	40	248.05	0.47	246.63	0.29
C	50	248.01	0.44	244.77	0.21
C	60	244.38	0.49	241.35	0.25
C	70	238.22	0.48	237.61	0.31
L	0	249.46	0.56	250.79	0.27
L	10	231.89	1.02	223.10	1.49
L	20	229.06	1.15	220.87	1.60
L	30	234.20	0.97	218.60	1.16
L	40	243.85	1.35	212.21	1.37
L	50	248.46	3.22	268.34*	1.53
L	60	250.63	1.96	211.15*	4.56
L	70	229.76	1.42	202.40	1.25

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	16.06	18.25	18.07

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
11.15	10.97	11.31

Date: 10/29/79 Time: 1010-1047

Plot No.: 1 Field: Corn (1)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	230.83	0.59	219.02	0.88
C	10	226.29	0.50	225.02	0.27
C	20	227.15	0.51	221.41	0.32
C	30	234.12	0.47	219.37	0.25
C	40	242.71	0.46	218.31	0.29
C	50	251.37	0.55	217.35	0.27
C	60	260.86	0.53	212.62	0.30
C	70	263.94	0.49	215.87	0.33
L	0	244.41	1.00	236.67	1.53
L	10	242.68	1.19	229.91	1.38
L	20	243.00	1.09	224.84	1.53
L	30	243.65	0.92	217.05	1.37
L	40	245.04	1.15	209.40	1.83
L	50	245.70	1.30	200.57	1.70
L	60	248.68	1.13	185.08	1.34
L	70	242.80	1.47	169.94	1.68

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	13.52	13.56	13.35

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
19.30	14.39	11.22

Date: 10/29/79 Time: 1051-1128

Plot No.: 2 Field: Soybean (1)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	252.10	0.42	253.45	0.31
C	10	250.85	0.52	252.71	0.32
C	20	246.03	0.60	248.21	0.24
C	30	247.98	0.53	248.32	0.27
C	40	250.98	0.44	247.41	0.22
C	50	253.46	0.54	247.13	0.28
C	60	251.44	0.54	244.80	0.26
C	70	244.99	0.53	241.81	0.21
L	0	242.07	1.69	225.55	1.62
L	10	238.26	1.23	222.77	1.40
L	20	238.48	1.05	217.30	1.55
L	30	234.37	1.05	212.95	1.48
L	40	236.80	1.25	213.04	1.55
L	50	240.98	1.05	237.25*	1.74
L	60	244.81	1.21	201.20	1.36
L	70	240.05	0.99	194.33	1.63

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	19.01	17.12	17.12

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
18.05	12.36	9.44

Date: 10/30/79 Time: 0800-0834

Plot No.: 1 Field: Corn (1)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	245.71	0.52	247.16	0.77
C	10	245.06	0.55	246.47	0.27
C	20	244.71	0.56	241.33	0.28
C	30	247.24	0.49	239.49	0.31
C	40	251.28	0.53	239.34	0.24
C	50	256.57	0.48	239.21	0.28
C	60	260.68	0.49	237.42	0.32
C	70	262.61	0.48	238.24	0.36
L	0	251.14	1.51	238.28	1.50
L	10	249.97	1.29	234.57	1.63
L	20	248.44	1.13	229.11	1.43
L	30	246.50	1.07	223.77	1.65
L	40	249.99	1.37	215.61	1.44
L	50	244.69	1.48	205.66	1.42
L	60	248.81	1.31	194.48	1.55
L	70	246.90	1.28	180.25	1.30

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	12.50	12.87	13.44

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
9.25	7.86	8.08

Date: 10/30/79 Time: 0837-0915

Plot No.: 2 Field: Soybean (1)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	249.89	0.52	250.60	0.28
C	10	249.16	0.50	250.28	0.29
C	20	248.34	0.45	250.04	0.34
C	30	248.53	0.45	247.61	0.29
C	40	251.44	0.47	248.31	0.29
C	50	252.49	0.50	248.35	0.29
C	60	251.59	0.50	245.88	0.28
C	70	245.17	0.54	241.84	0.25
L	0	238.57	1.32	229.73	1.50
L	10	228.96	1.44	225.26	1.28
L	20	238.57	1.11	221.17	1.44
L	30	240.64	1.13	215.21	1.43
L	40	238.02	1.16	208.23	1.41
L	50	238.19	3.58	200.07	1.47
L	60	248.36	1.12	197.31	1.31
L	70	243.05	1.27	193.44	1.24

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	17.07	16.68	16.22

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
12.55	9.72	8.39

Date: 10/30/79

Time: 0918-1045

Plot No.: 1

Field: Cut Corn (Bare)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	231.25	0.48	231.86	0.26
C	10	227.06	0.47	224.34	0.31
C	20	225.35	0.63	217.79	0.27
C	30	227.89	0.58	210.49	0.31
C	40	235.06	0.53	204.68	0.30
C	50	246.03	0.53	192.31	0.30
C	60	253.12	0.59	176.76	0.37
C	70	254.72	0.57	161.59	0.76
L	0	232.28	1.02	222.70	1.61
L	10	222.42	0.98	219.05	1.23
L	20	229.65	1.16	212.14	1.22
L	30	229.40	1.94	206.57	1.52
L	40	229.42	1.19	194.94	1.67
L	50	236.65	1.14	182.23	1.35
L	60	251.49	1.13	163.77	1.23
L	70	242.55	1.72	133.03	1.55

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	12.62	12.43	13.04

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
13.90	10.53	9.47

Date: 10/30/79 Time: 1049-1128

Plot No.: 2 Field: Cut Soybean (Bare)

Freq.	Angle	Average A.T. (V)	Standard Dev. (V)	Average A.T. (H)	Standard Dev. (H)
C	0	235.42	0.57	236.45	0.36
C	10	227.33	0.57	225.78	0.30
C	20	226.15	0.61	220.82	0.29
C	30	230.87	0.49	215.68	0.25
C	40	237.30	0.60	206.73	0.26
C	50	245.92	0.59	192.03	0.34
C	60	253.15	0.56	173.96	0.41
C	70	250.30	0.54	144.50	0.43
L	0	226.64	1.04	223.52	1.51
L	10	215.43	1.10	210.24	1.62
L	20	214.39	1.14	203.74	1.42
L	30	219.21	1.18	195.39	1.51
L	40	228.50	2.58	186.09	1.34
L	50	231.24	1.21	223.54*	1.40
L	60	241.37	3.00	150.51	1.35
L	70	238.15	2.36	119.14	1.47

Soil Moisture Data (%)

0-0.50 cm	0-2.5 cm	2.5-5 cm	5-10 cm
–	16.57	16.22	16.58

Soil Temperature Data (°C)

2.5 cm above	0-2.5 cm	10-12.5 cm
18.50	16.25	10.83

Table 1
L-band radiometer parameters

Frequency	1400 to 1427 MHz
R.F. Bandwidth	27 MHz
System Noise Figure	3 db
R.F. Insertion Loss	$\simeq$ 0.75 db
Integration Time Constant	0.1 sec
Temperature Sensitivity	$\Delta T \leqslant 0.5\ ^\circ K$
Radiometer Calibration Constant	$\simeq$ 15 mv/°K
Stability	
Radiometer Ambient Temperature	Controlled at 43°C

BIBLIOGRAPHIC DATA SHEET

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15. Supplementary Notes

16. Abstract

An experiment on the remote sensing of soil moisture content by microwave radiometers mounted on a mobile tower was carried out during October 1979 over bare and vegetated fields in a test site of Beltsville Agricultural Research Center (BARC). Two microwave radiometers were used in the experiment, one of them at 1.4 GHz (L-band) and the other at 5 GHz frequencies. Both radiometers measured the field brightness temperatures over 10°-70° incident angles in vertical and horizontal polarizations simultaneously. Five types of fields were included in the measurements, namely, bare, 10-cm tall orchard grass, 30-cm tall orchard grass, soybean, and corn. Ground truth soil moisture content and temperature, as well as the biomass of the vegetations was acquired in support of the microwave radiometric measurements.

This document describes the operational principle of various sensors and date system. It also gives a tabulation of the measured data and a brief discussion on the problems associated with the sensors. A preliminary analysis of the measured data is also given. The results show that the measured brightness temperatures at both L and C bands decrease with the increase in soil moisture content, in general agreement with the observations of the past. The presence of the vegetation cover generally gives a higher brightness temperature than that expected from a bare field when soil is not dry. As a consequence, the sensititivy of microwave soil moisture sensing is reduced.

17. Key Words (Selected by Author(s))	18. Distribution Statement
Soil Moisture, Remote Sensing	

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